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INDEX

1 - Introduction	2
2 - Statistical Sampling	2
3 - Functions of Comprehensive Distribution	3
4 - Annual Variability in the Distribution Function	4
5 - Monthly Variability in the Distribution Function	5
6 - Relationships Between the Annual Statistics and the Worst Month	5
7 - Conclusions	7
8 - Bibliography	10
9 - Tables	11
10 - Drawings	13

1. Introduction

In the period of May 1974 to April 1977, within the scope of the ISPT-FUB research program on radio propagation at frequencies greater than 10 GHz [B1]*, measurements of attenuation due to rain were carried out continually in the Fucino Experimental Center in an interval between 9.5 Km at frequencies from 11 to 128 GHz in vertical polarization and 128 GHz in horizontal polarization. For the methods of performing the measurements and the accuracy obtained see [B2].

The present paper reports on the cumulative distribution functions of the attenuation found in the three connections. The differences between the distribution functions and the different polarization frequencies are demonstrated. Particular attention is devoted to the possibility of establishing a bond between the statistics of annual attenuation and worst month attenuation. This relationship assumes particular importance in view of the methods with which quality objectives in radio systems are generally expressed in international centers.

2. Statistical Sampling

In the period of May 1974-April 1977, during which continuous attenuation measurements were made, approximately 120 rainy situations were found: of these 72 produced an attenuation greater than 8 dB in the 17.8 GHz connection in horizontal polarization, and of these 72 significant incidents, some were

* The notation [B] indicates the References.

not used because they were unavailable as a result of difficulties found in the reception system. Table I shows the number of significant situations used and not used, distributed to year and connection. The remaining 48 events, during which attenuation in the 17.8 GHz connection in the horizontal polarization remained below 8 dB, have been inserted into the statistical elaborations.

The elaboration of the data consisted of evaluating the statistical distribution function of the attenuation due to the rain defined as:

$$P [A > A_j] = \frac{\sum_{i=1}^{N_j} T_{ji}}{T_{\text{tot}}} \cdot 100.$$

where, with reference to Figure 1:

$P [A > A_j]$ is the probability that the attenuation due to rain exceeds the value A_j , expressed as a percentage of the total observation time;

T_{ji} is the individual duration of excess over the value A_j , defined as in Figure 1; and

T_{tot} is the total observation time.

3. Functions of Comprehensive Distribution

Figure 2 presents, for the three connections, the distribution functions obtained from the data received during the entire observation period of 8 years.

The difference between attenuation at 17.8 or 11 GHz in vertical polarization, exceeded for the same percentage of time, increases as probability diminishes, i.e., as attenuation increases. The difference between attenuation in horizontal and vertical polarization at the same frequency of 17.8 GHz shows an analogous slope. It has been confirmed that the electromagnetic waves,

polarized horizontally, become more attenuated than those polarized vertically at the same frequency, and that the attenuation increases with the frequency, polarization being equal.

The saturation which the three curves demonstrate for percentages of excess, less by some seconds per year, is to be attributed to the limited number of situations which contribute to this portion of the distribution function.

In this respect the data contained in Table II are indicative, with the three connections and the various threshold values of attenuation given with the number of the individual periods of duration of excess (N_o) and the number of incidents (N_e) during which the threshold under consideration was exceeded. It is clear that several individual periods of excess can correspond to each situation.

4. Annual Variability in the Distribution Function

Figures 3, 4 and 5 show the functions of distribution relative to the individual years for the 3-year period of observation for each connection.

For all three connections the annual variability turns out to be very subject to percentages greater than 10^{-2} for the time of year, increasing while the percentage of the excess time diminishes. Such a variability is due to the limited number of incidents which contribute to exceeding the high attenuation values. However, a 3-year period of observation cannot be considered sufficient to define in a statistically significant way the slope of the distribution function relative to percentages of time shorter than several tens of minutes per year.

5. Monthly Variability in the Distribution Function

Figures 6-14 present the monthly distribution functions (January - 1, December - 12) and the annual ones for each of the three connections and for each of the three years of observation.

In all of the cases mentioned the months which are the major contributors to the annual distribution function vary from year to year, but are found between June and November in every year.

For the two 17.8 GHz connections for every year, the most significant months are precisely coincident. For the 11 GHz connection, the most significant months in the first two years are not precisely the same as those for the 17.8 GHz connections. Since the connections are in the same interval, this is attributed to the fact that some of the situations not used in the statistics are not the same in the three cases.

What has been said above calls attention to the effect of intensive incidents on the slope of the distribution function and on the special caution to be exercised in drawing statistical conclusions based on the relationships between the same distribution function.

6. Relationships Between the Annual Statistics and the Worst Month

In view of the considerable variability from one year to another, the attenuation statistics for a certain connection are generally presented on an annual base and referred to a multiyear period of observation. On the other hand the quality objectives for the telecommunications systems are generally referred to percentages of the time of "any month" of the year. Therefore

it is necessary to specify a bond between annual statistics and worst month statistics.*

In general this relationship is established by means of the factor:

$$Q = \frac{P_{mp}}{P_a}$$

which expresses the relationship between the probability that the same attenuation value will be exceeded in the worst month (P_{mp}) and in the year (P_a). In general the slope of the factor Q is expressed as a function of the percentage of the worst month and the year.

Intuitively the value of Q can vary from 1 (when the attenuation value considered is exceeded with the same probability in all 12 months) to 12 (when the attenuation value considered is exceeded in only a single one of the months of the year).

For each of the three connections Figures 15-17 show the statistical distribution relative to the average year and to the average worst month in the 3-year period of observation.

Figures 13-20 represent the values of Q as a function of the percentage of the year and the single years of the survey.

For each connection Figures 21-23 give the mean values of the factor Q as a function of the annual percentage found either in the average distributions

* This is understood as statistical distribution in the worst month for a definite year, not necessarily solar, the range of the twelve monthly distribution functions.

of the worst month and of the year (Figures 15-17) or as the mean of the three values of Q relative to the individual years (Figures 16-20). It can be noted from Figures 21-23 that the values of Q obtained with the two procedures are very similar to one another.

In order to investigate the possibility that a single slope of Q as a function of the annual percentage can be representative for all three connections, Figure 24 presents the mean values of Q for the three connections. It can be seen that these values are very similar. This indicates that a single mean slope of Q can be representative of all three connections. This mean slope is presented as a function of the annual percentage in Figure 25 and as a function of that of the worst month in Figure 26.

The fact that a single slope of Q can be representative of the three connections at various frequencies and polarization in the same interval can be explained by considering that the relationships among the specific attenuation, calculated in a theoretical way for the frequencies and polarization considered, prove to be almost constant.

On the basis of the experimental data relating to the mean distribution functions in Figure 2, the extent of such relations has been calculated, and are presented in Figure 27 as a function of the annual percentage. This figure convinces us that the relative constancy of these relationships is also confirmed experimentally. No comparison between the experimental relationships and those calculated theoretically has been attempted so far, since the experimental distribution functions assumed as the basis of the calculations do not strictly include the same incidents. Such a comparison and the implicit eventual confirmation of the specific attenuation values

theoretically calculated will be the subject of a later study in which precisely the same events will be taken into consideration for all three connections.

According to what has been said, the slope of Q relative to the attenuation on terrestrial connections should depend only on the distance of the connection and not on the frequency or polarization used.

For the purpose of comparison Figure 26 shows, in addition to the slope of the factor Q relative to attenuation, its typical slope for the average European situation with respect to the intensity of exact precipitation [B3]. The statistical sampling referred to is the slope of the factor Q for attenuation measured from 9 distributions/year, while the sampling relative to the slope of Q for the intensity of exact precipitation, derived from measurements made in Italy, Great Britain, Austria and Holland, is made up of 31 distributions/year and can be considered sufficiently representative of the mean European situation.

It can be seen from the figure that the slope of Q relative to the attenuation almost coincides with the slope relative to the intensity of exact precipitation up to worst month percentages equal to 10^{-1} (%), while it proves to be greater than the latter for lower percentages of time.

7. Conclusions

Confirmation has been obtained that, for a definite connection, attenuation due to rain for a fixed percentage of time increases as frequency increases, and is greater in horizontal polarization than in vertical polarization.

The annual variability in the distribution function of the three connections proves to be quite subject to the time of the year referred to for percentages lower than 10^{-2} (%), while it increases for lower values of

this percentage. In view of the considerable influence which a limited number of incidents can have on the relationships of the distribution function, the conclusion is drawn that an observation period of several years is necessary in order to define in a statistically significant way the attenuation for percentages of time lower than several tens of minutes per year.

In all of the three connections a considerable variability has been found in the distribution function based on the month. The months which most contribute to the annual distribution function vary from year to year, but prove to occur between June and November in every year.

The bond between the annual and the worst month statistics can be expressed with a single slope for all three connections operating in the same interval. It turns out that for such connections the mean relationship between the worst month percentage and the annual percentage (referred to the same attenuation value) varies from approximately 4 to approximately 9 percent of the time, referred to the worst month, and between 3×10^{-1} and 10^{-2} (%) respectively. According to what has already been said, the slope of Q relative to the attenuation on terrestrial connections should depend only on the distance of the connection and not on the frequency or polarization used.

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1. F. Fedi, B. Peroni: Research Program on the Propagation of Waves with a Frequency Above 10 GHz, May-June 1970.
2. F. Fedi, P. Migliorni: Services of the Attenuation Measuring System for the Interval from 11 to 17.8 GHz. Internal Paper.
3. F. Fedi: Rainfall Characteristics across Europe. Final Report of the COST 25/4 management committee, E. C. Commission, January 79.

① Collegamento	11.5 Hz. (V.P.)		17.3 Hz. (H.F.)		17.8 GHz. (V.P.)	
	② Eventi		② Eventi		② Eventi	
	③ Utilizzati	④ non utilizzati	③ Utilizzati	④ non utilizzati	③ Utilizzati	④ non utilizzati
⑤ 1° anno 5/74 + 4/75	19	1	20	-	20	-
⑤ 2° anno 5/75 + 4/76	19	1	17	3	18	2
⑤ 3° anno 5/76 + 4/77	32	-	29	3	29	3
⑥ Totale 3 anni	70	2	66	6	67	5

Table I. Number of Significant Incidents Used and Not Used

Key: 1-Connection, 2-Incidents, 3-Used, 4-Not used, 5-Year, 6-3-year total.

² Frequenza (GHz)	¹¹ ² pol. verticale		^{17.8} ² pol. verticale		^{17.0} ³ pol. orizzontale	
⁴ Attenuazione (dB)	N _e	N _D	N _e	N _D	N _e	N _D
10	7	20	38	83	48	136
18	2	3	14	24	22	54
30	—	—	5	6	7	22
42	—	—	—	—	3	7
50	—	—	—	—	2	3

Table II. Number of Incidents (N_e) and Individual Duration (N_D) of Excess for Various Attenuation Values

Key: 1-Frequency, 2-Vertical polarization, 3-Horizontal polarization, 4-Attenuation

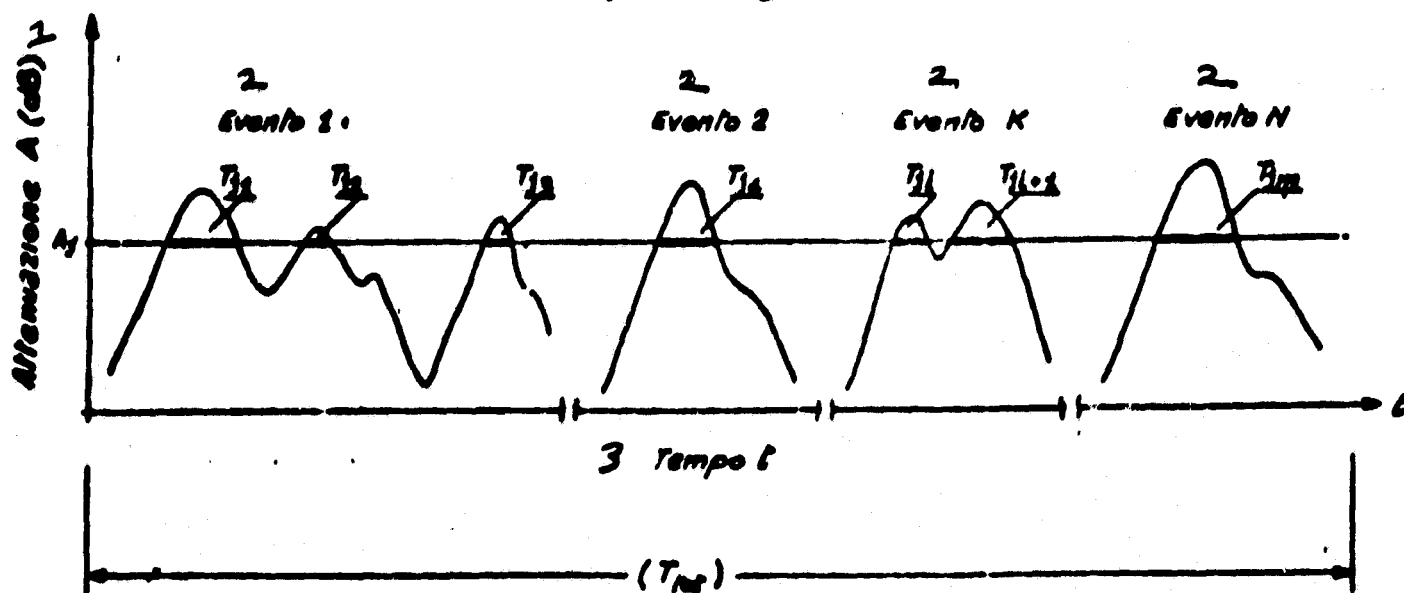


Figure 1. Incidents and Individual Length of Excess T_{j1} .

Key: 1-Attenuation A, 2-Incident, 3-Time.

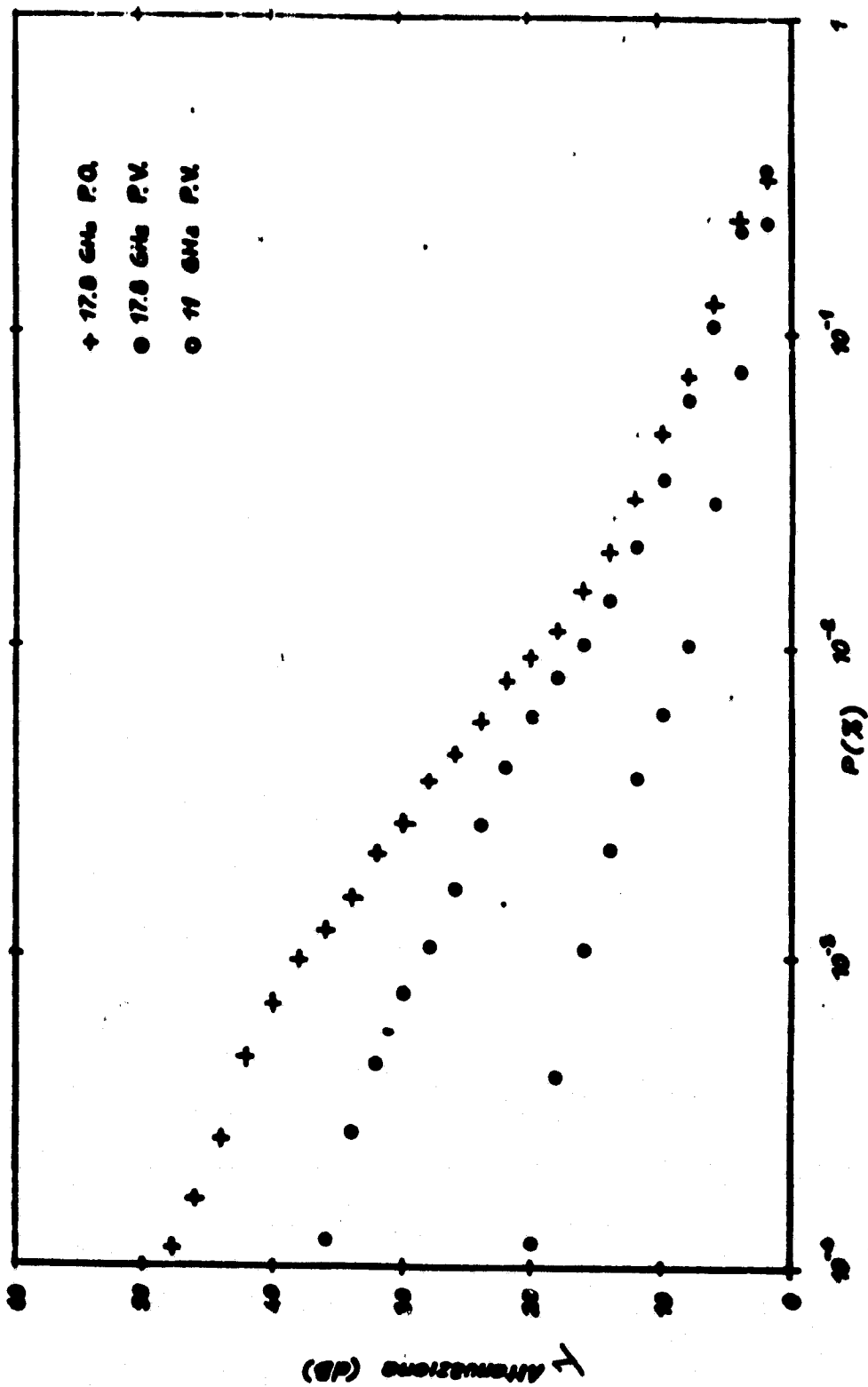


Figure 2. Cumulative Annual Distribution Functions of Attenuation Relative to the Period 5/74-4/77.

Key: 1-Attenuation.

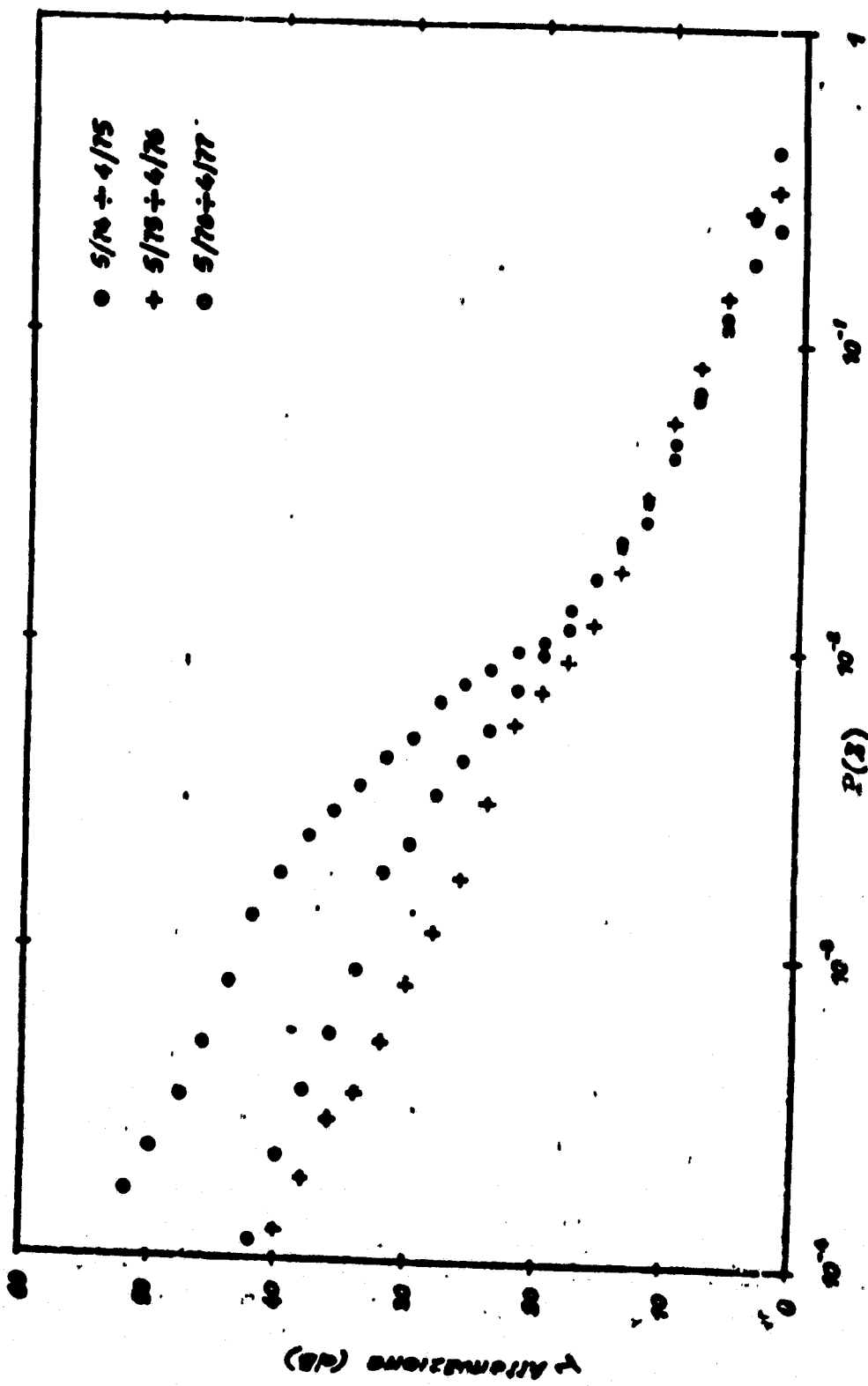


Figure 3. Annual Distribution Functions of Attenuation at Frequency 17.8 GHz in Horizontal Polarization.

Key: 1-Attenuation.

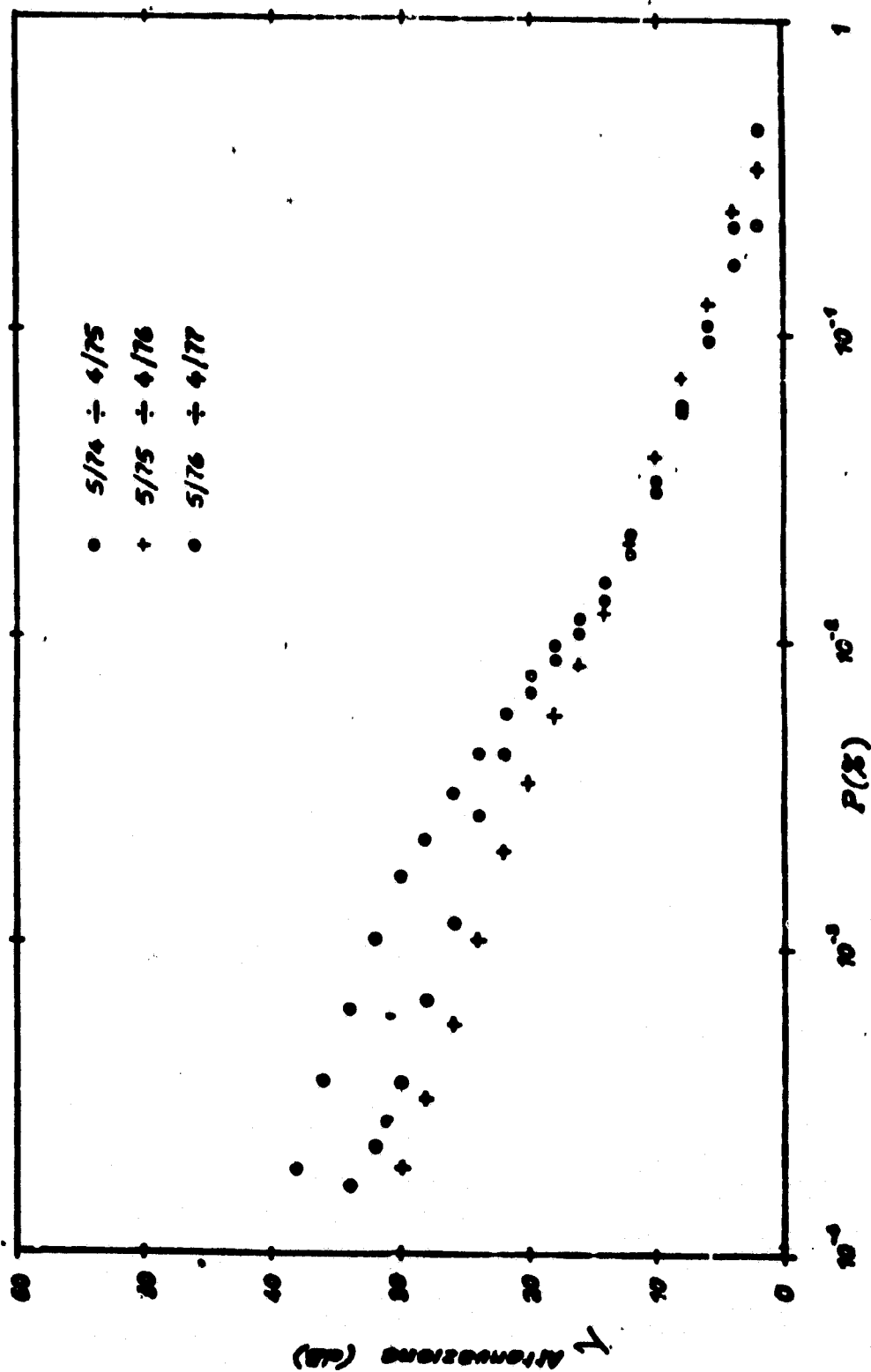


Figure 4. Annual Distribution Functions of Attenuation at Frequency 17.8 GHz in Vertical Polarization

Key: 1-Attenuation

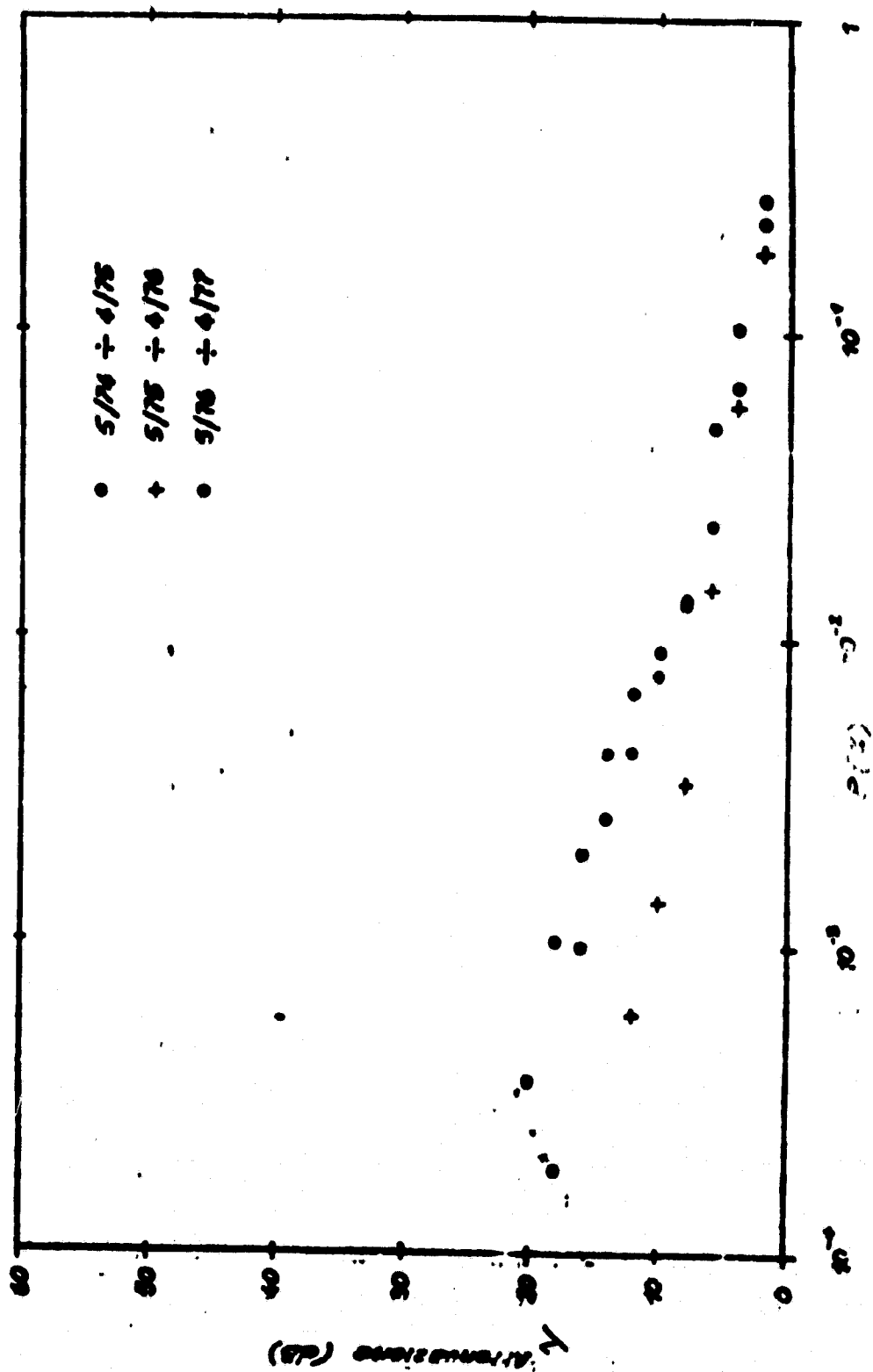


Figure 5. Annual Distribution Functions of Attenuation at Frequency 11 GHz in Vertical Polarization.

Key: 1-Attenuation

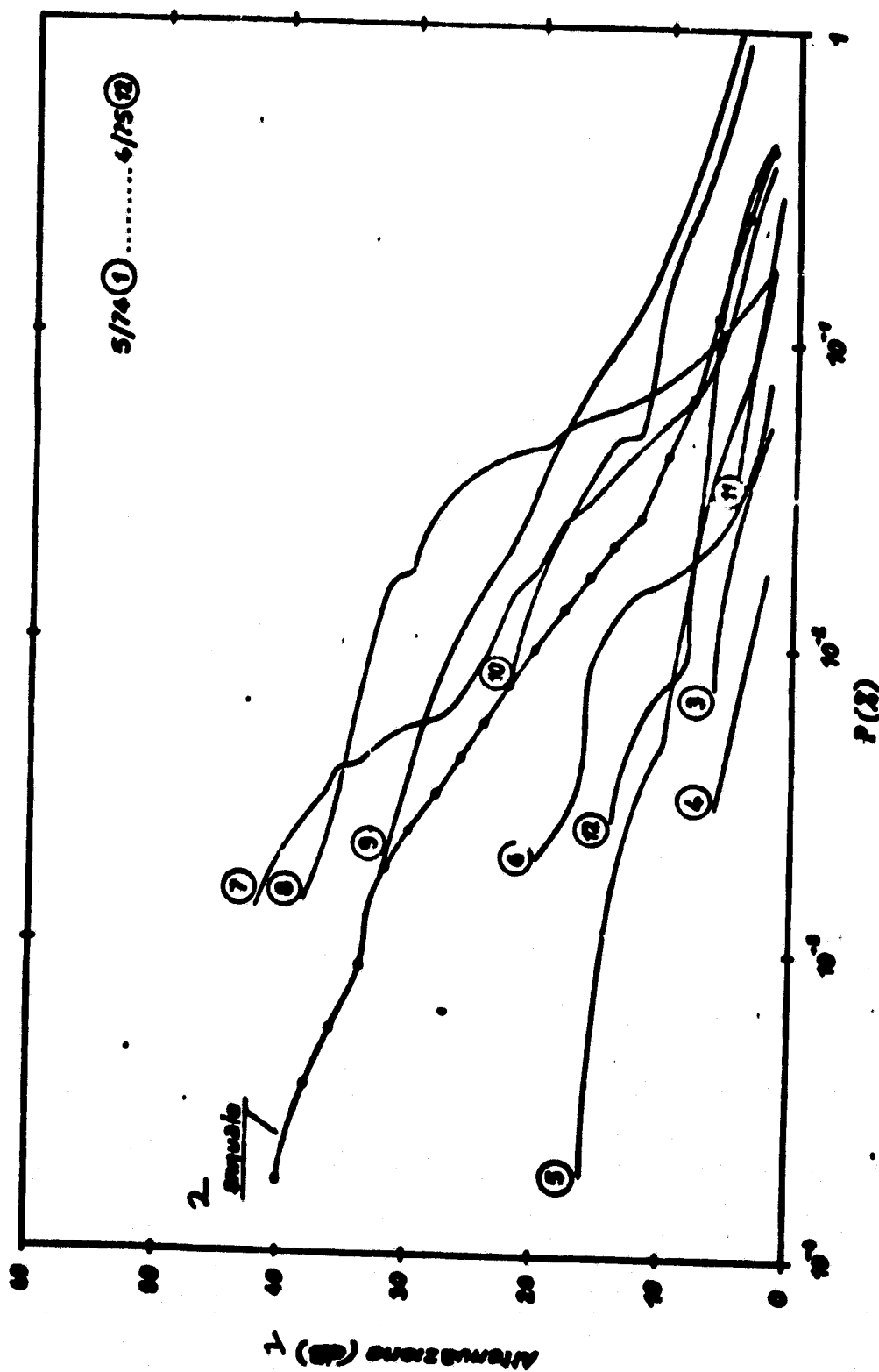


Figure 6. Monthly, Annual and Worst Month Distribution Functions of Attenuation at Frequency 17.8 GHz in Horizontal Polarization (Period 5/74-4/75).

Key: 1-Attenuation, 2-Annual

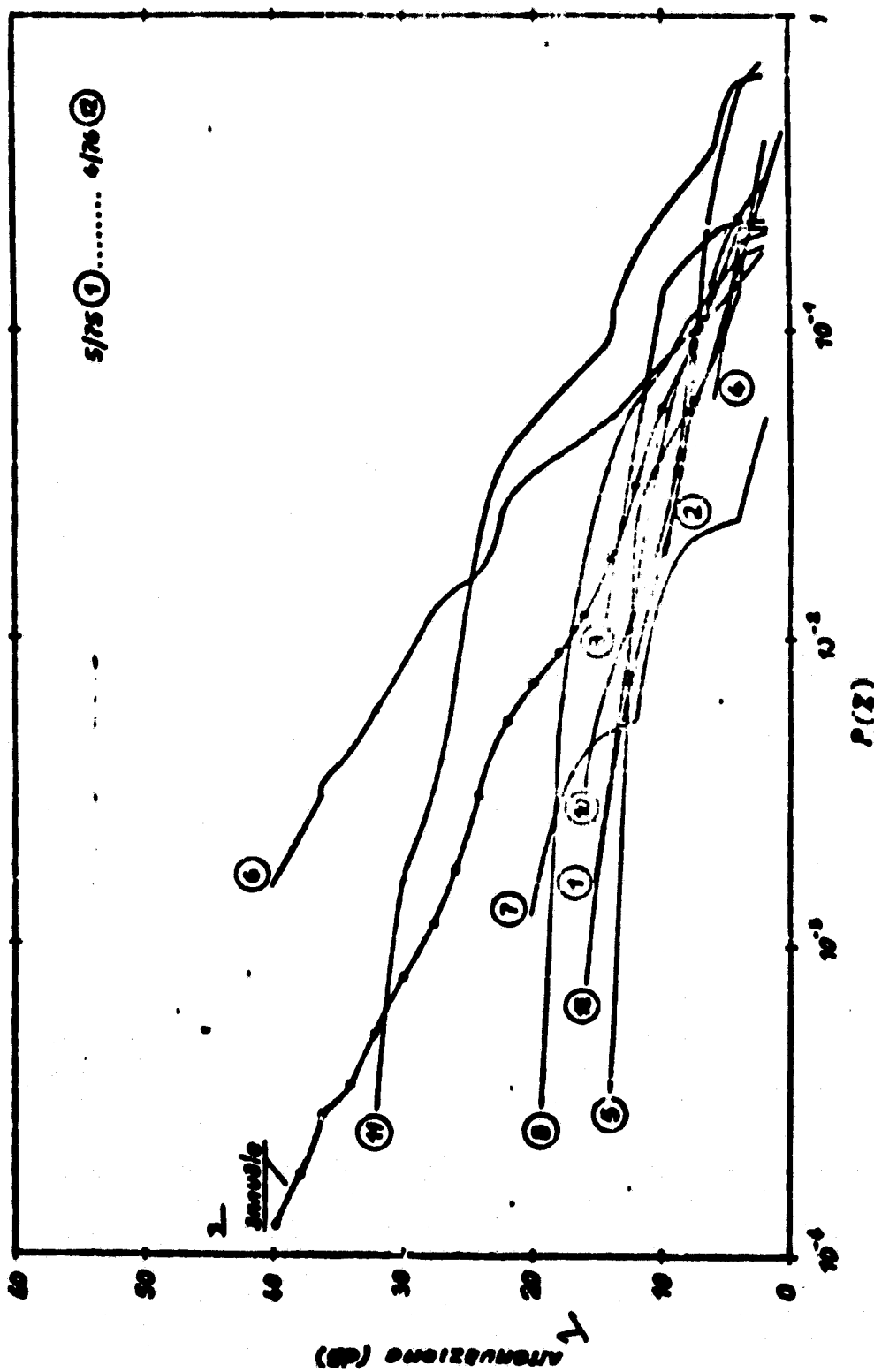


Figure 7. Monthly, Annual and Worst Month Distribution Functions of Attenuation at Frequency 17.8 GHz in Horizontal Polarization (Period 5/75-4/76).

Key: 1-Attenuation, 2-Annual

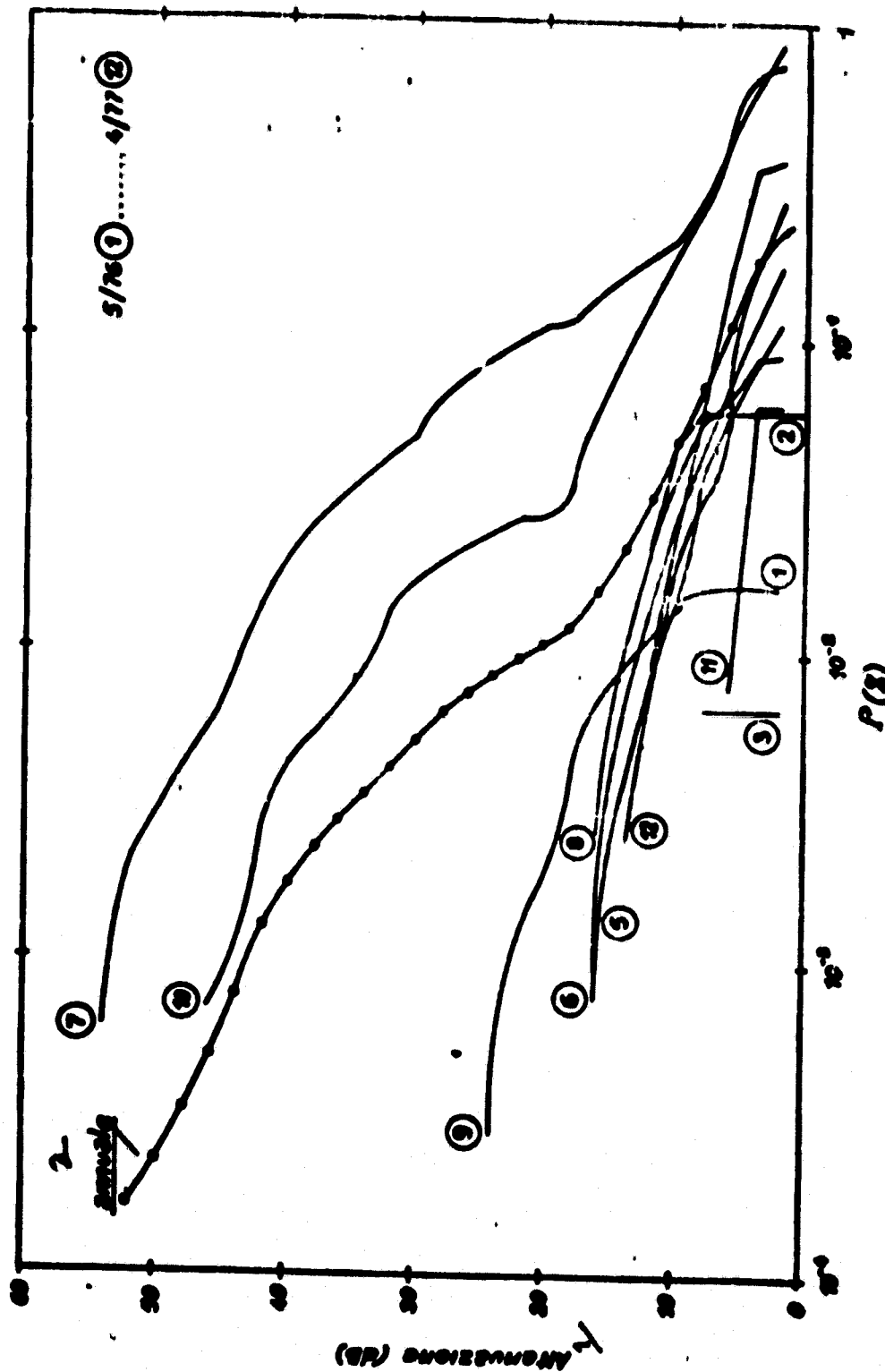


Figure 8. Monthly, Annual and Worst Month Distribution Functions of Attenuation at Frequency 17.8 GHz in Horizontal Polarization (Period 5/76-4/77).
Key: 1-Attenuation, 2-Annual

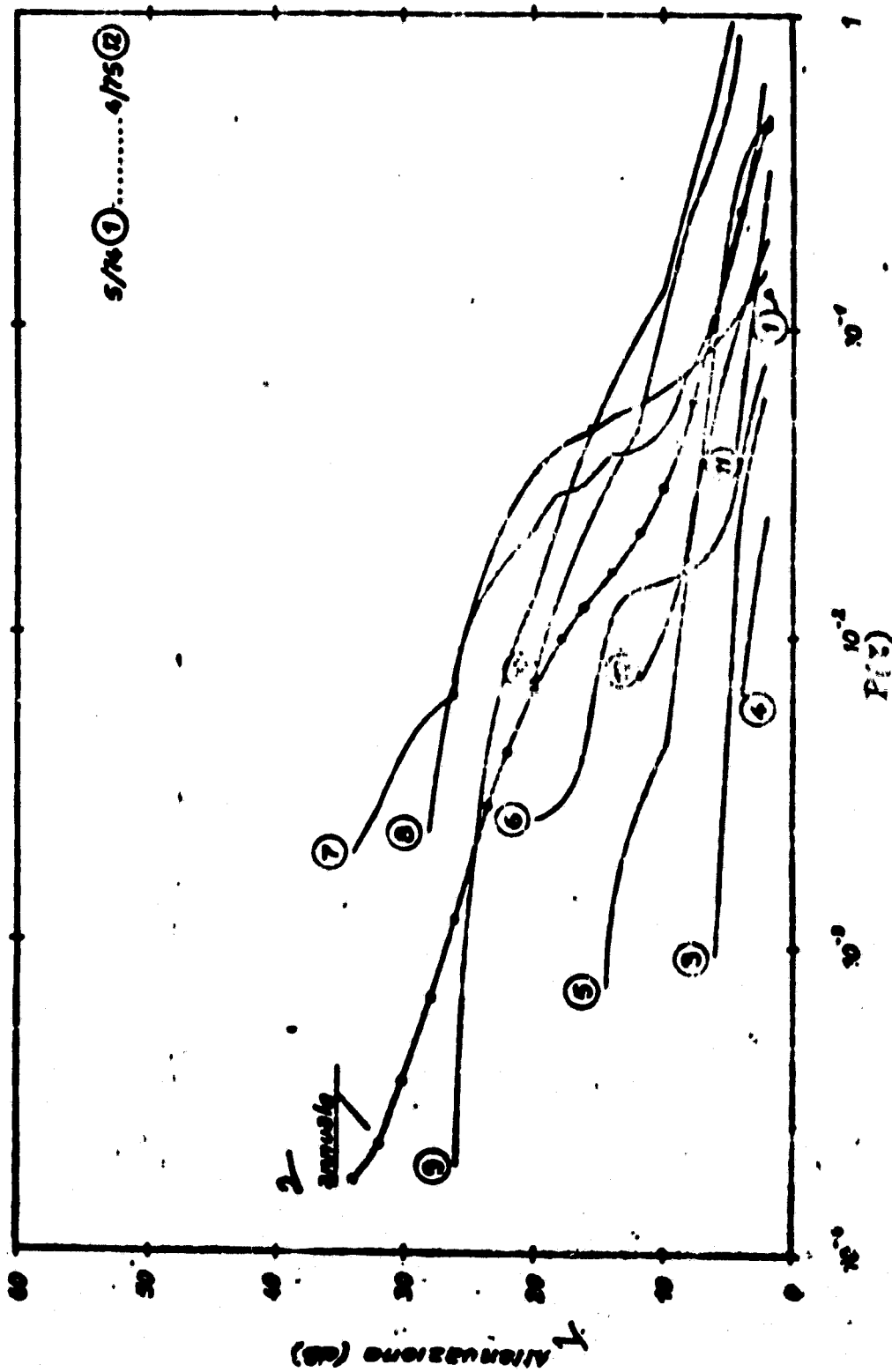


Figure 9. Monthly, Annual and Worst Month Distribution Functions of Attenuation at Frequency 17.8 GHz in Vertical Polarization (Period 5/74-4/75).

Key: 1-Attenuation, 2-Annual

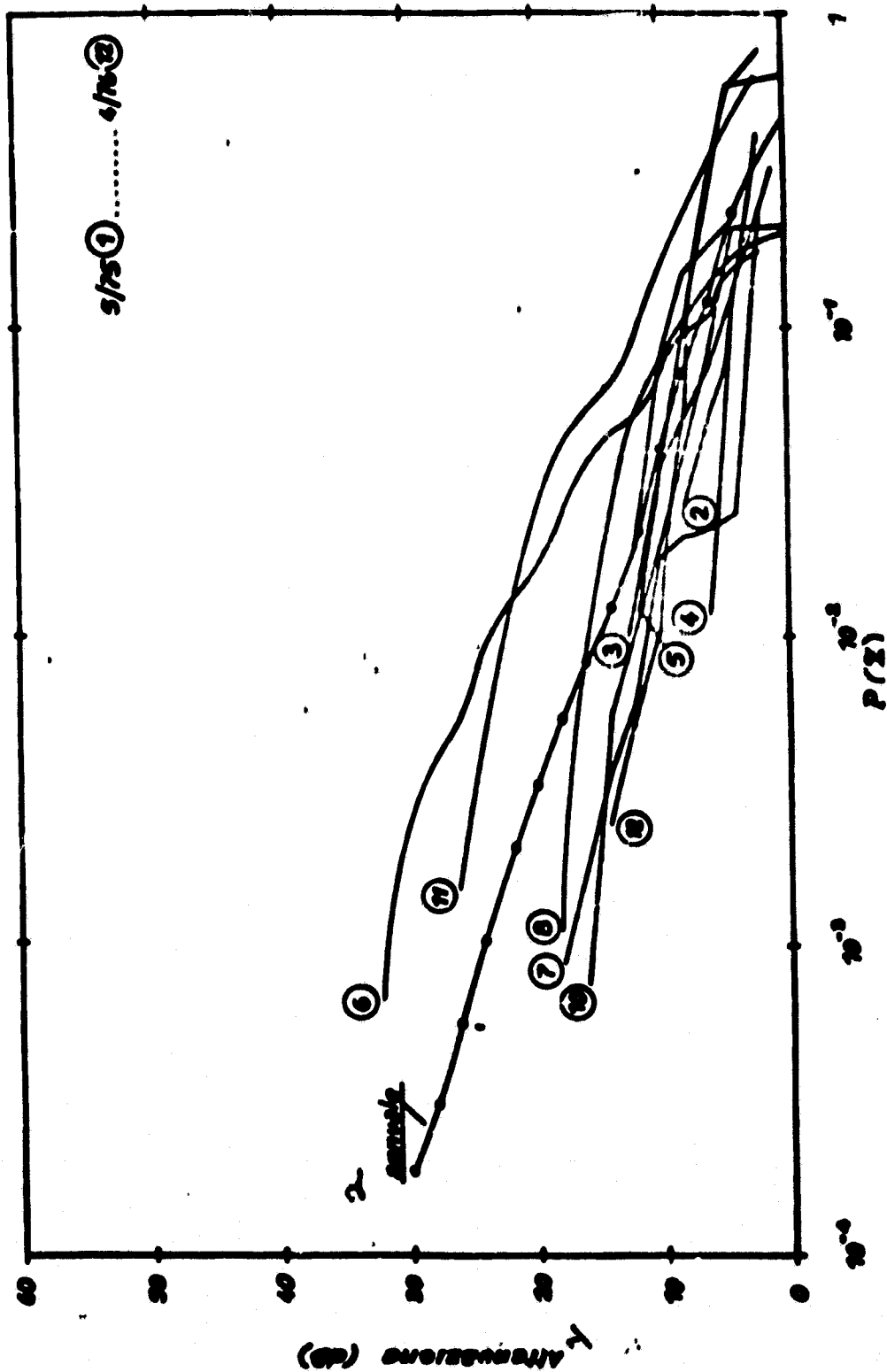


Figure 10. Monthly, Annual and Worst Month Distribution Functions of Attenuation at Frequency 17.8 GHz in Vertical Polarization (Period 5/75-4/76) . .

Key: 1-Attenuation, 2-Annual

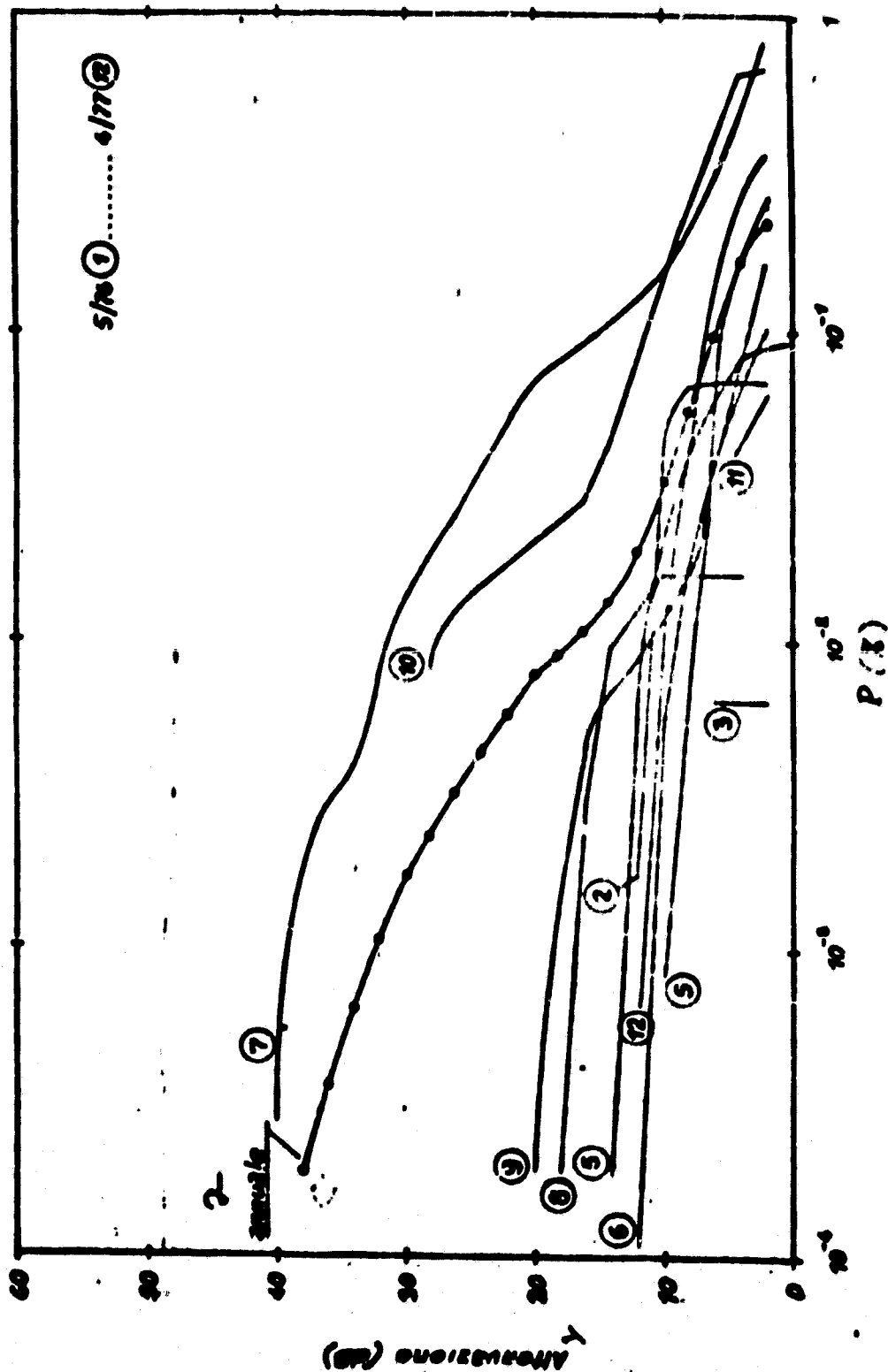


Figure 11. Monthly, Annual and Worst Month Distribution Functions of Attenuation at Frequency 17.8 GHz in Vertical Polarization (Period 5/76-4/77).

Key: 1-Annual, 2-Annual

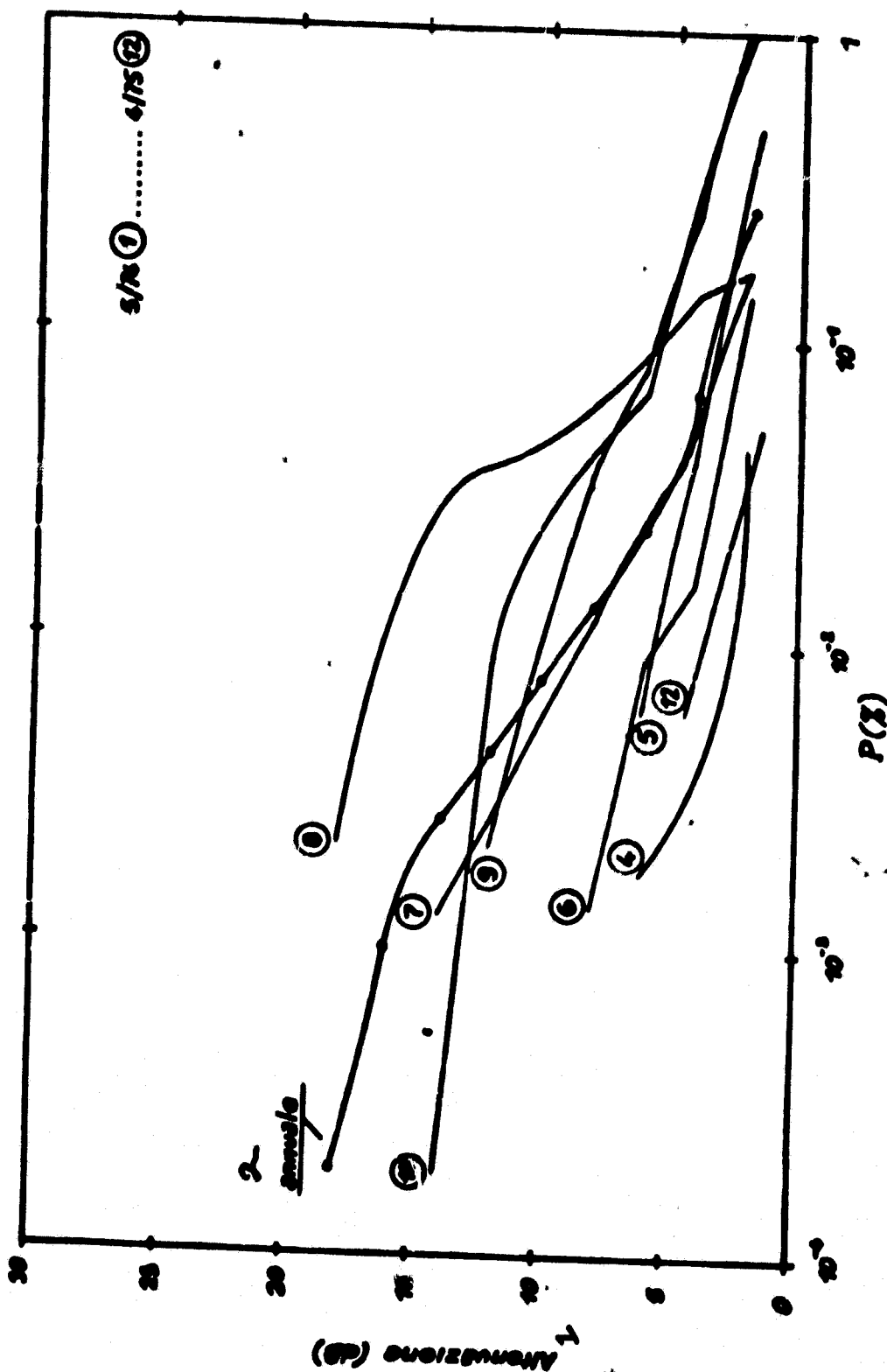


Figure 12. Monthly, Annual and Worst Month Distribution Functions of Attenuation at Frequency 11 GHz in Vertical Polarization (Period 5/74-4/75).

Key: 1-Attenuation, 2-Annual

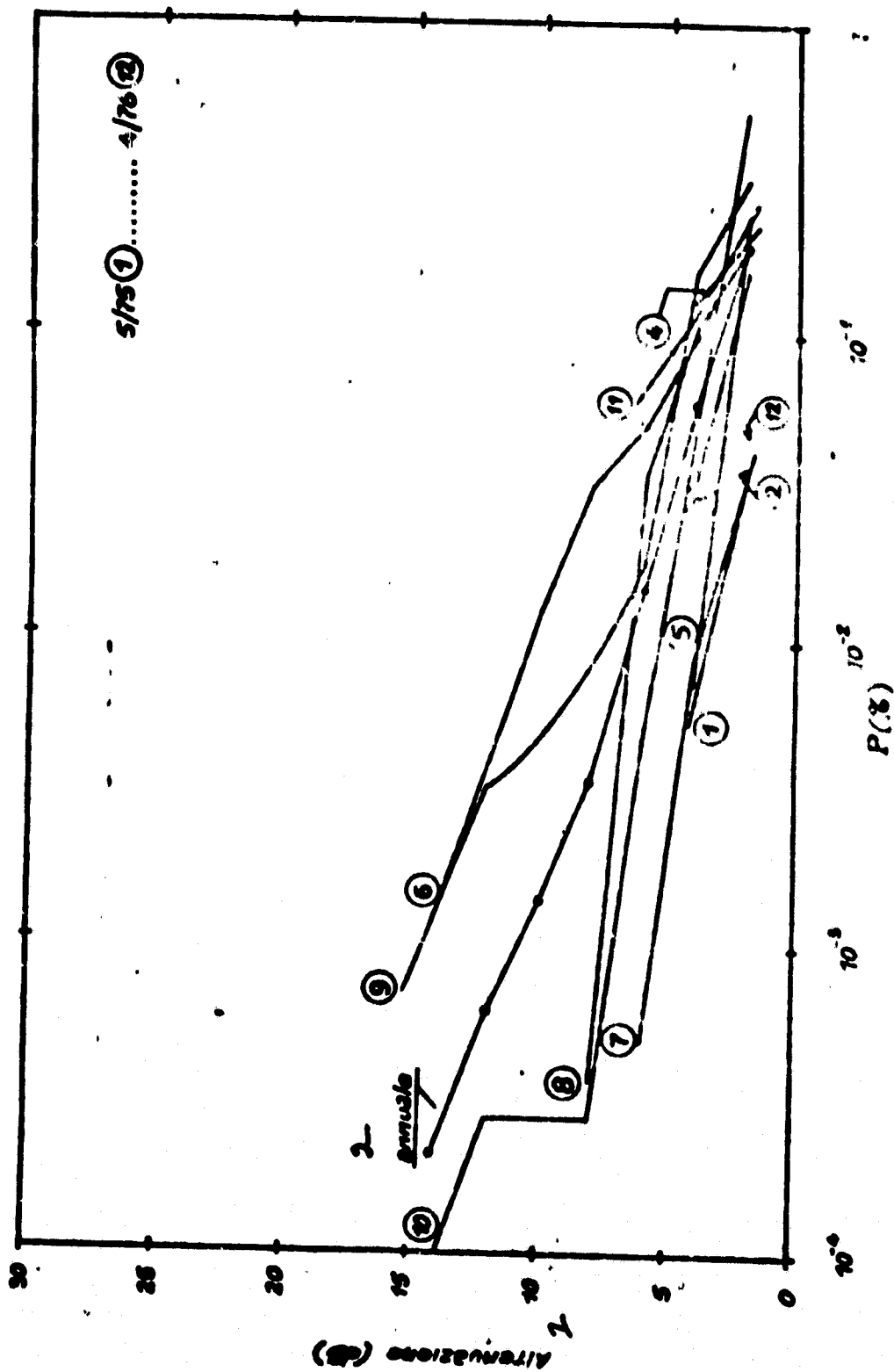


Figure 13. Monthly, Annual and Worst Month Distribution Functions of Attenuation at Frequency 11 GHz in Vertical Polarization (Period 5/75-4/76).

Key: 1-Attenuation, 2-Annual

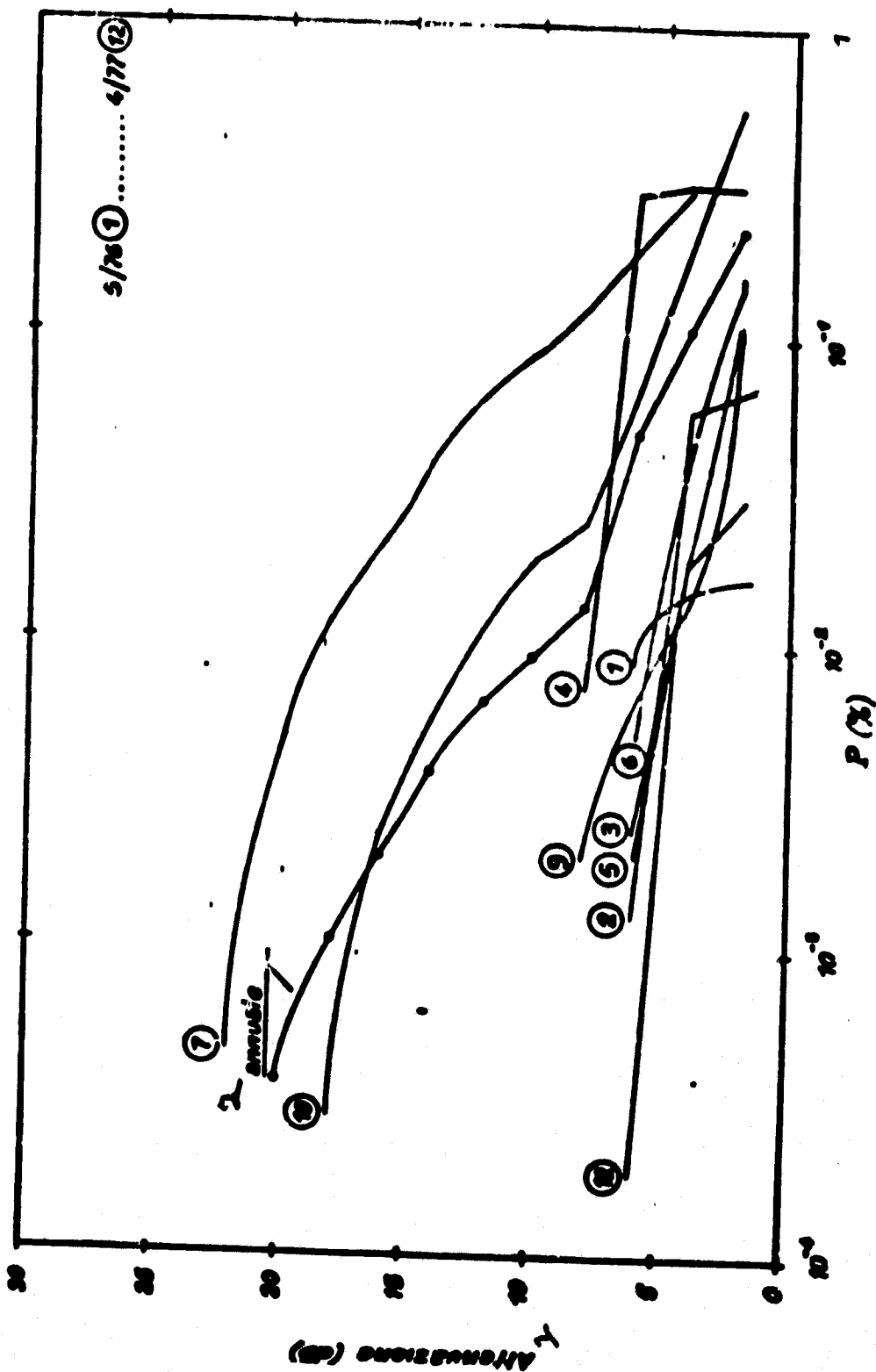


Figure 14. Monthly, Annual and Worst Month Distribution Functions of Attenuation at Frequency 11 GHz in Vertical Polarization (Period 5/76-4/77).

Key: 1-Annual, 2-Annual

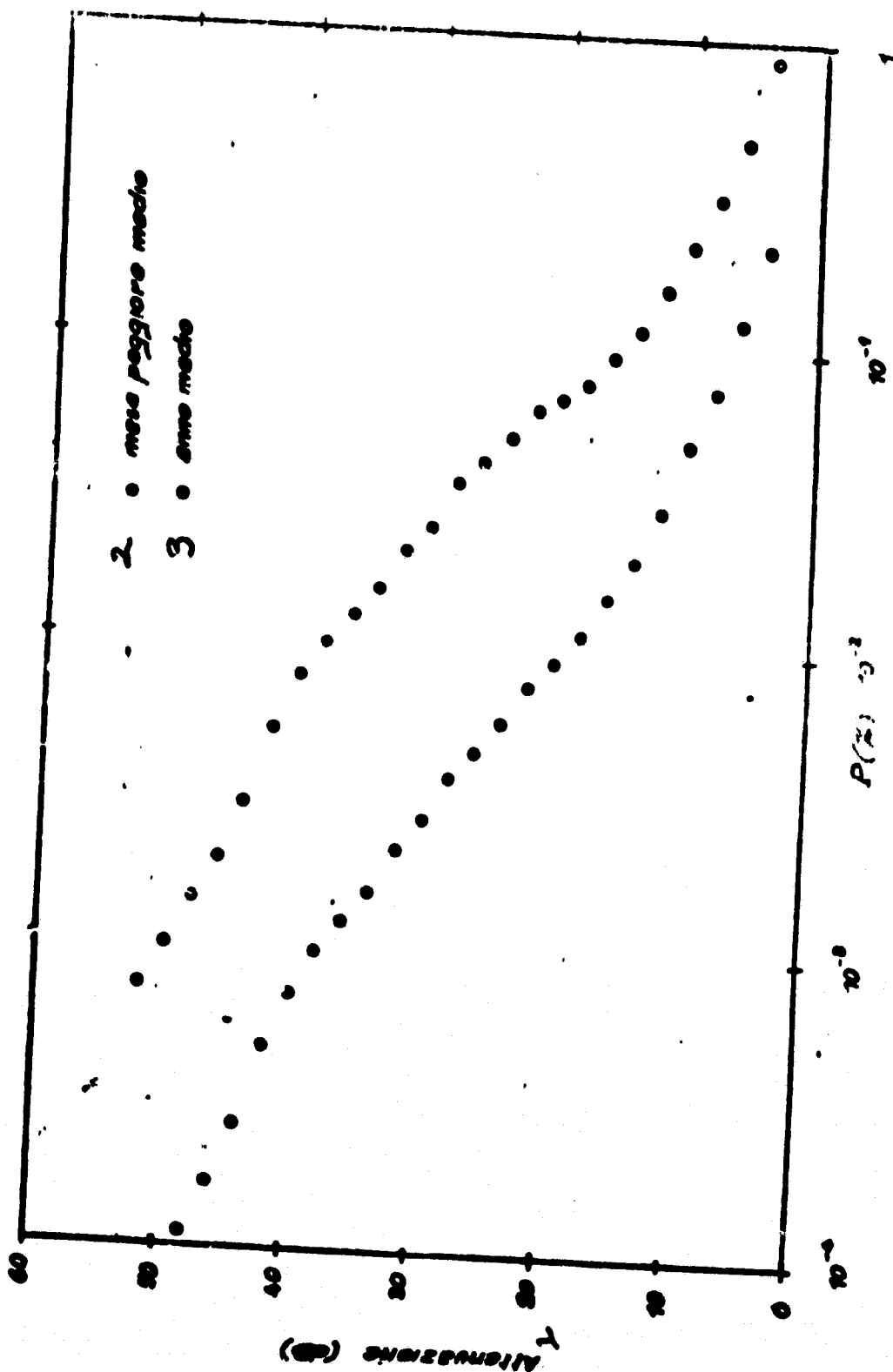


Figure 15. Cumulative Distribution Function of Attenuation at Frequency 17.8 GHz in Horizontal Polarization, Relative to the Average Year and the Average Worst Month (Period 5/74-4/77).

Key: 1-Attenuation, 2-Average worst month, 3-Average year.

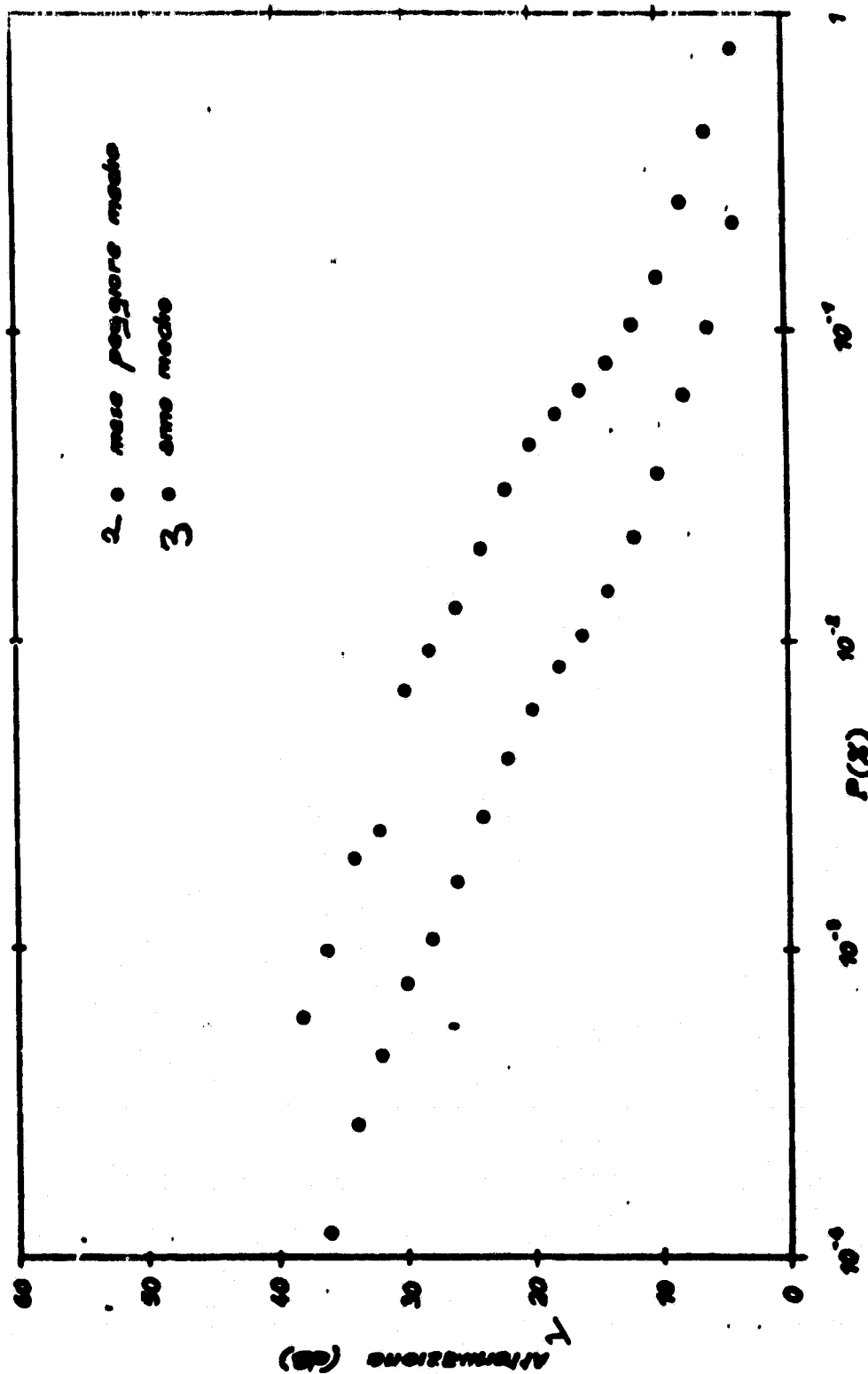


Figure 16. Cumulative Distribution Functions of Attenuation at Frequency 17.8 GHz in Vertical Polarization, Relative to the Average Year and the Average Worst Month (Period 5/74-4/77).

Key: 1-Attenuation, 2-Average worst month, 3-Average year.

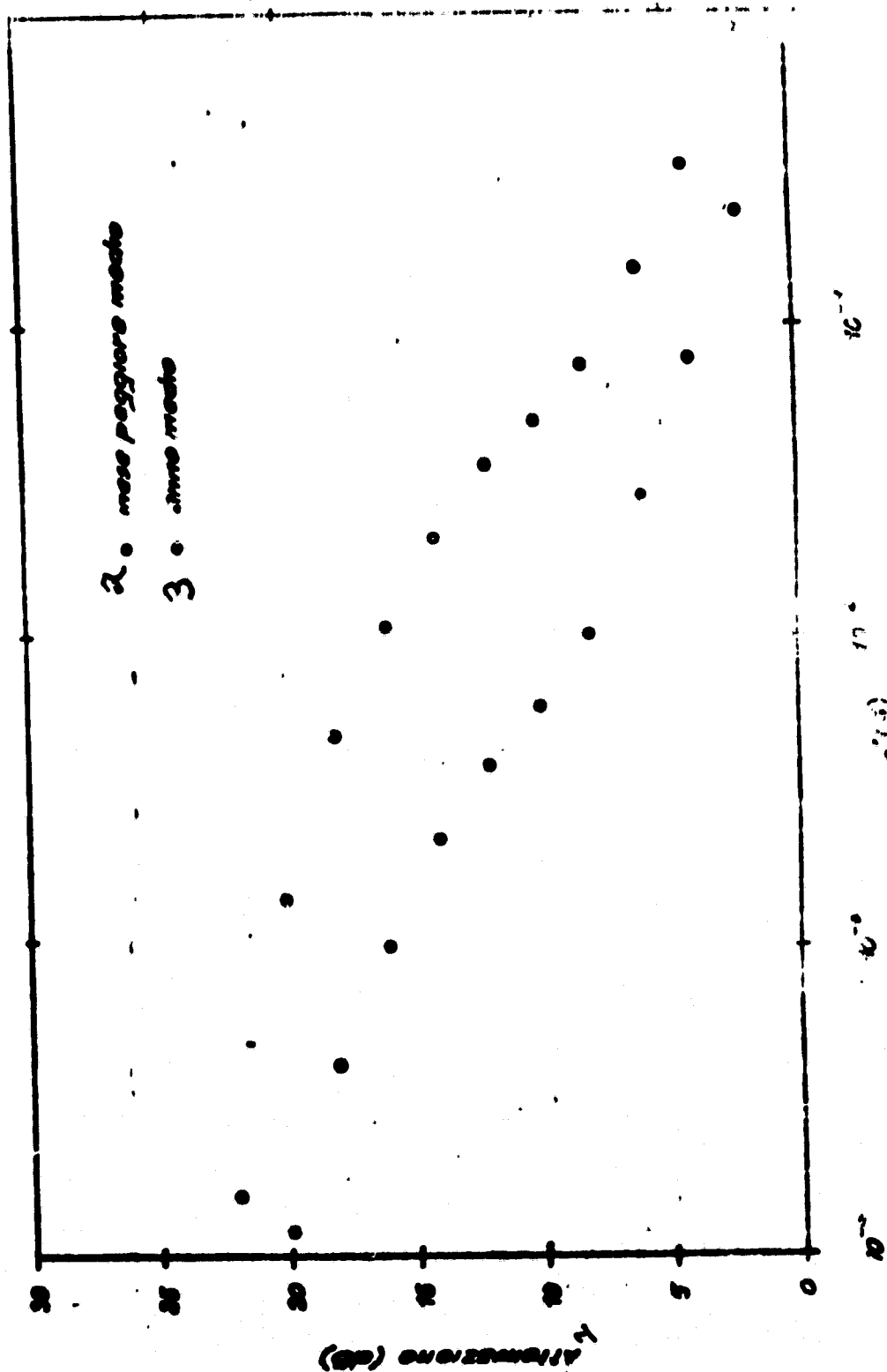


Figure 17. Cumulative Distribution Functions of Attenuation at Frequency 11 GHz in Vertical Polarization, Relative to the Average Year and Average Worst Month (Period 5/74-4/77).

Key: 1-Attenuation, 2-Average worst month, 3-Average year.

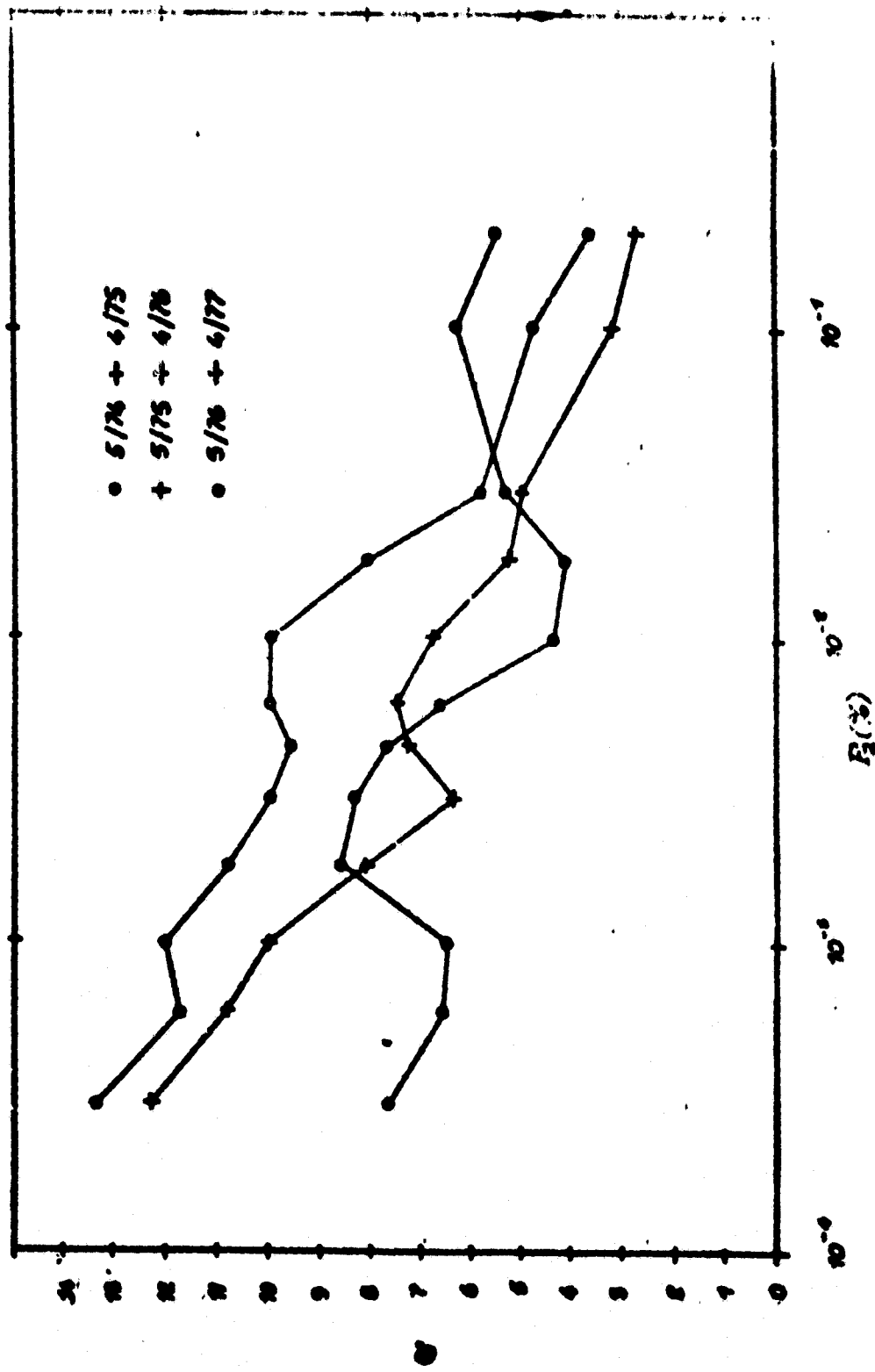


Figure 18. Slopes of Factor Q for Attenuation at Frequency 17.8 GHz in Horizontal Polarization.

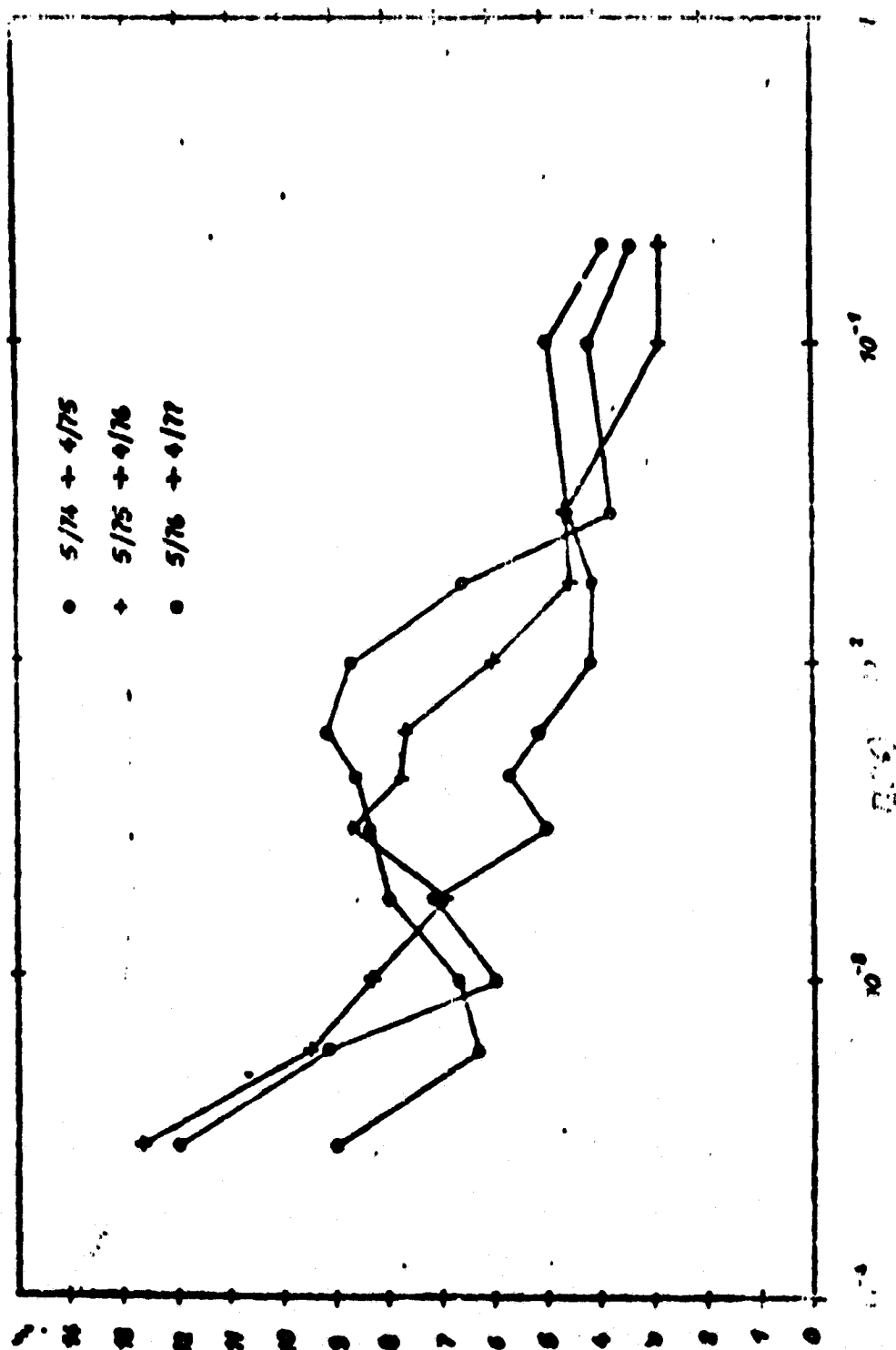


Figure 19. Slopes of Factor Q of Attenuation at Frequency 17.8 GHz in Vertical Polarization.

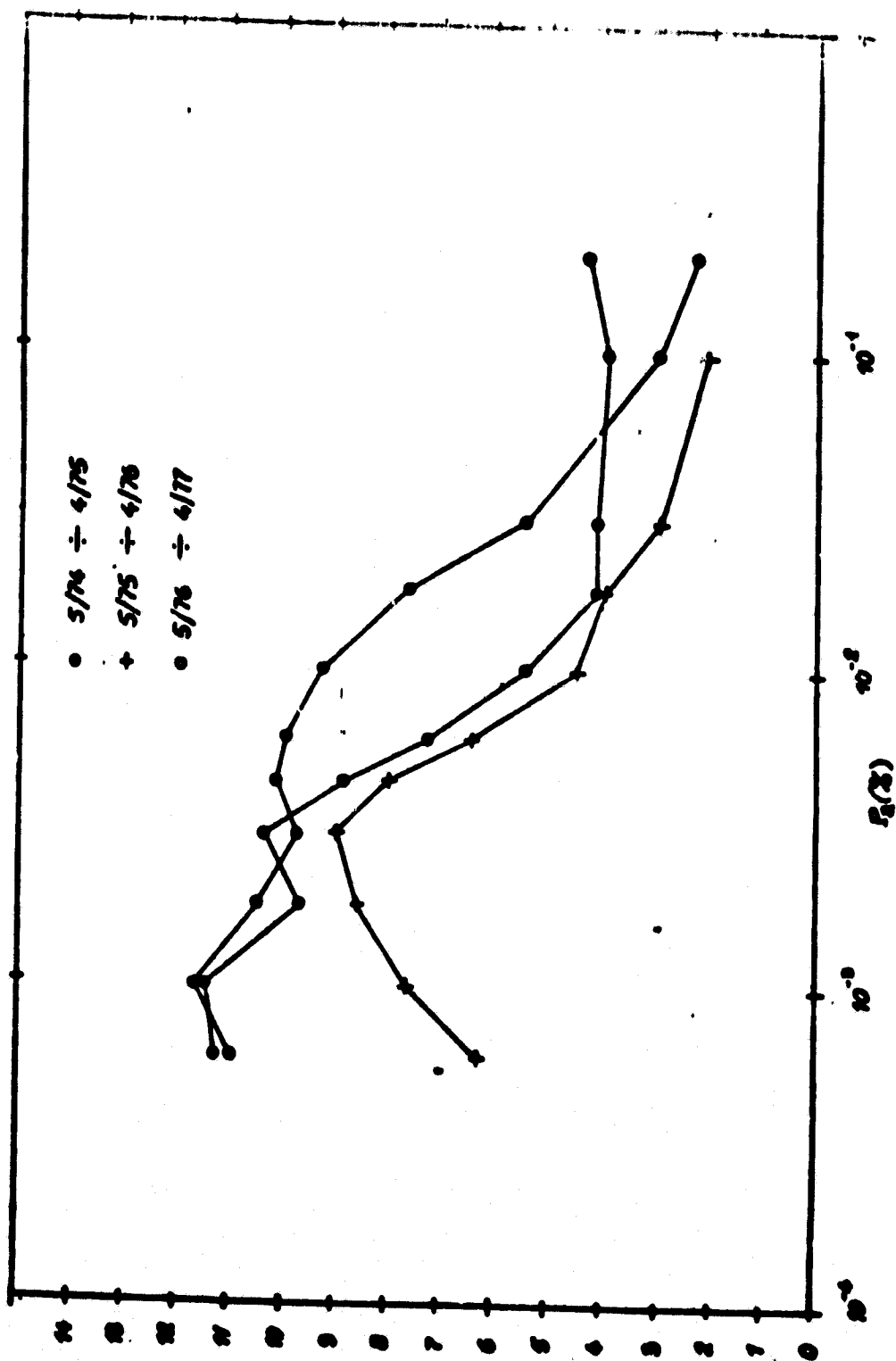


Figure 20. Slopes of Factor Q at Frequency 11 GHz in Vertical Polarization:

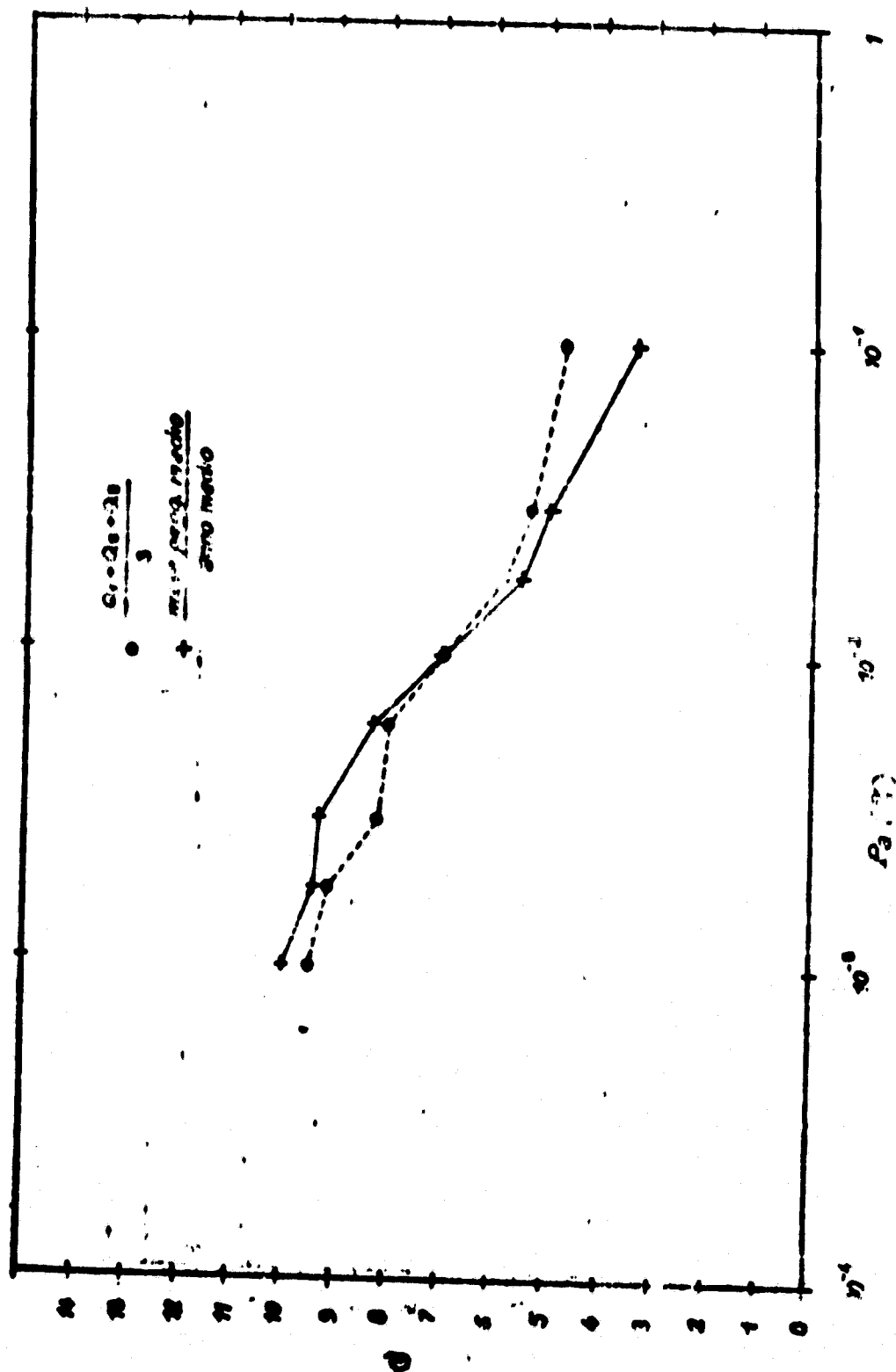


Figure 21. Mean Slopes of Factor Q of Attenuation at Frequency 17.8 GHz in Horizontal Polarization.

Key: 1-Mean worst month/mean year.

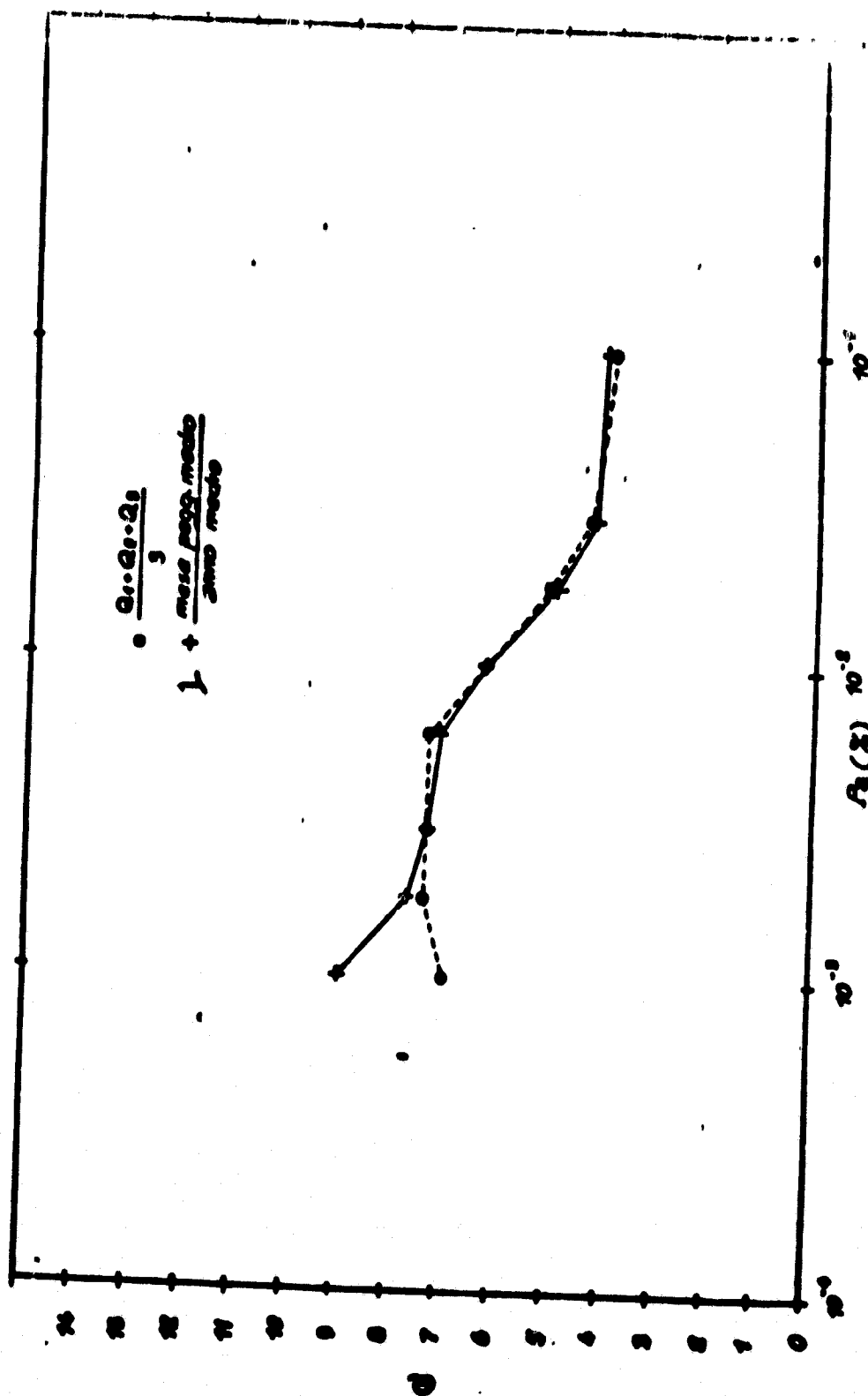


Figure 22. Mean Slopes of Factor Q of Attenuation at Frequency 17.8 GHz in Vertical Polarization.

Key: 1-Average worst month/average year.

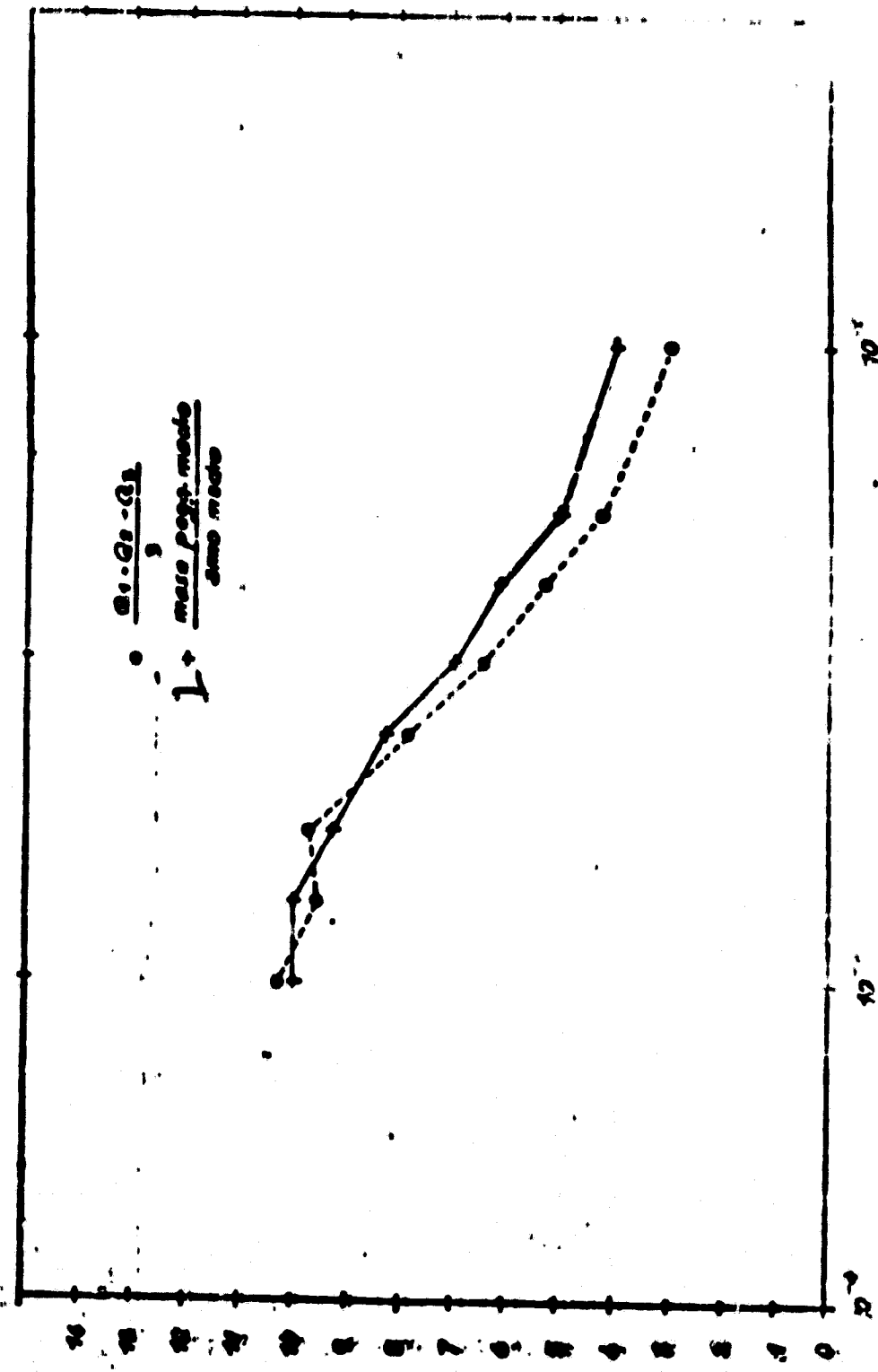


Figure 23. Mean Slopes of Factor Q of Attenuation at Frequency 11 GHz in Vertical Polarization.

Key: 1-Average worst month/average year.

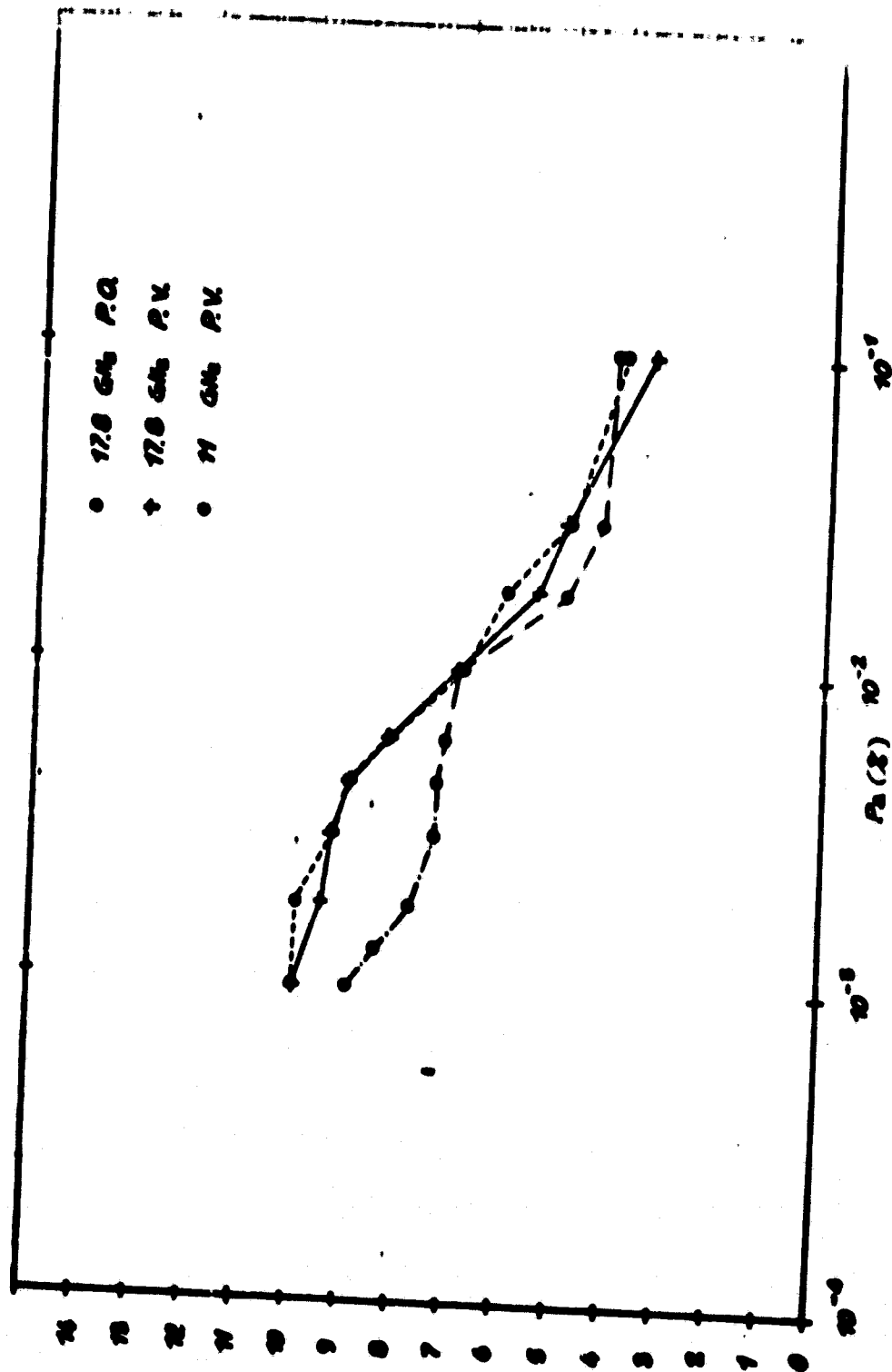


Figure 24. Mean Slopes of Factor Q, Derived from Mean Distribution of Worst Month and of Year.

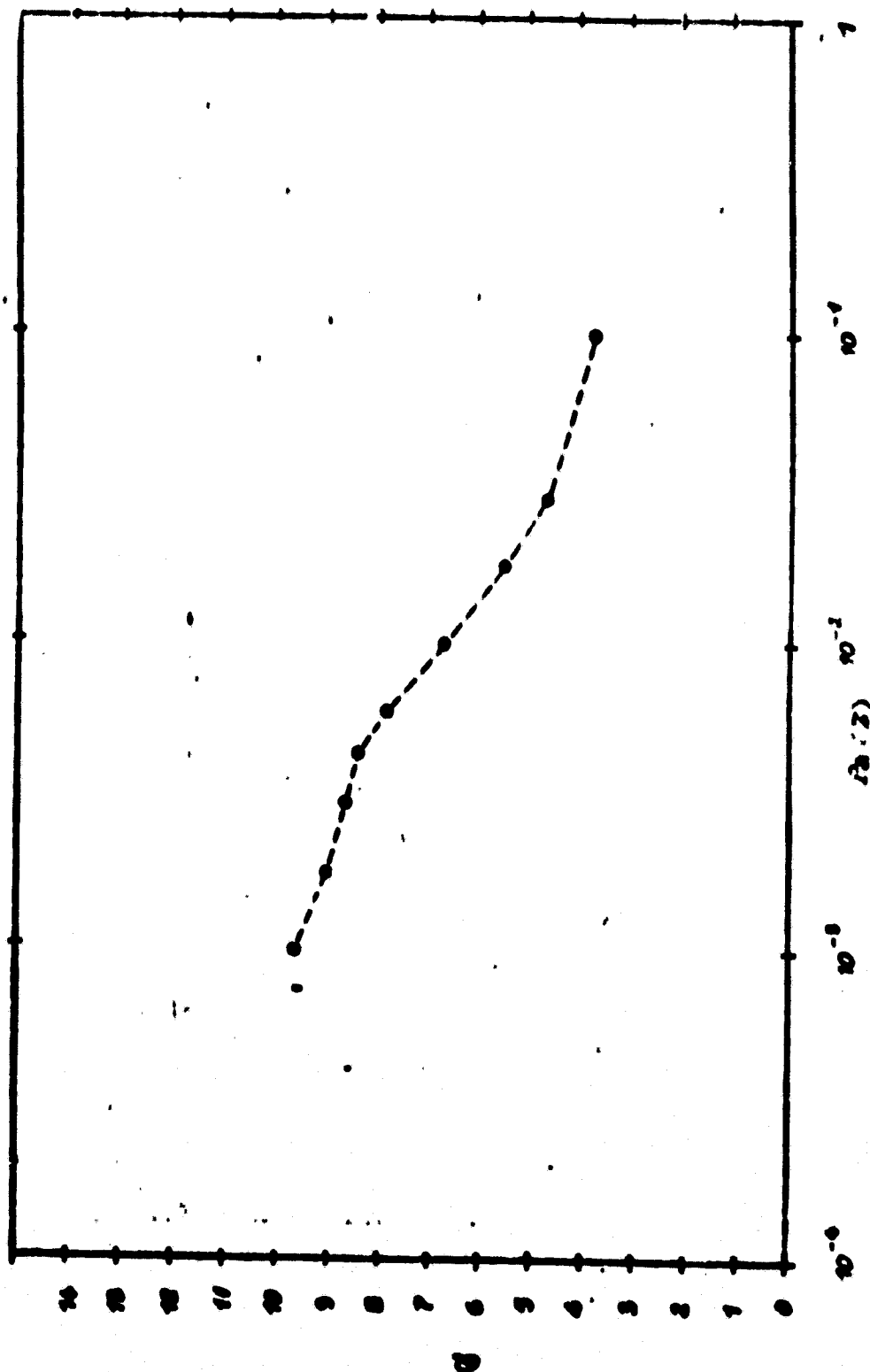


Figure 25. Mean Slope of Q Representative of Attenuation at 17.8 GHz in Horizontal and Vertical Polarization, and at 11 GHz in Vertical Polarization.

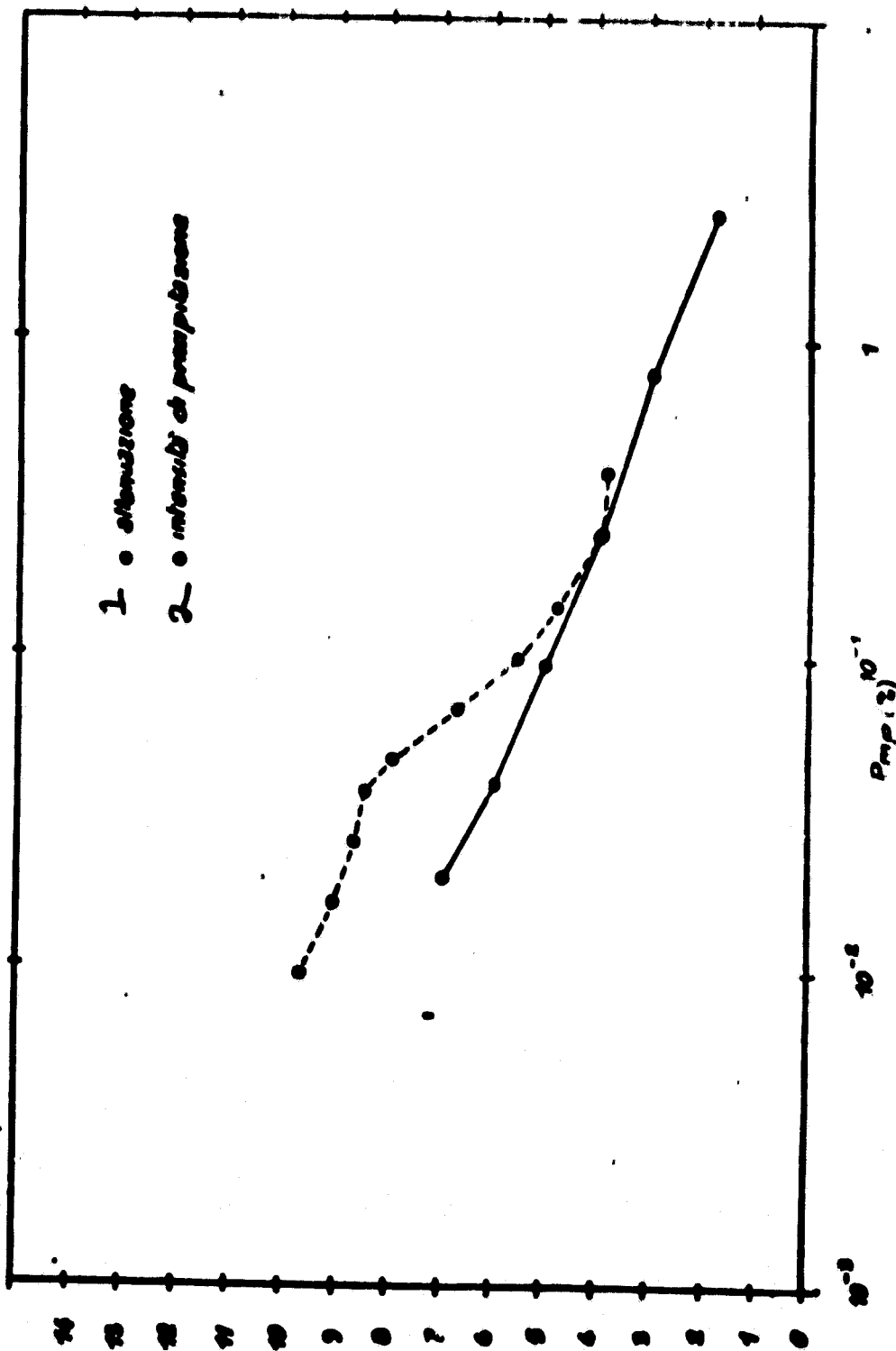


Figure 26. Mean Slope of Q for Attenuation Representative of [illegible word] and Connections, and Mean Precipitation Intensity of the European Situation.

Key: 1-Attenuation, 2-Precipitation intensity.

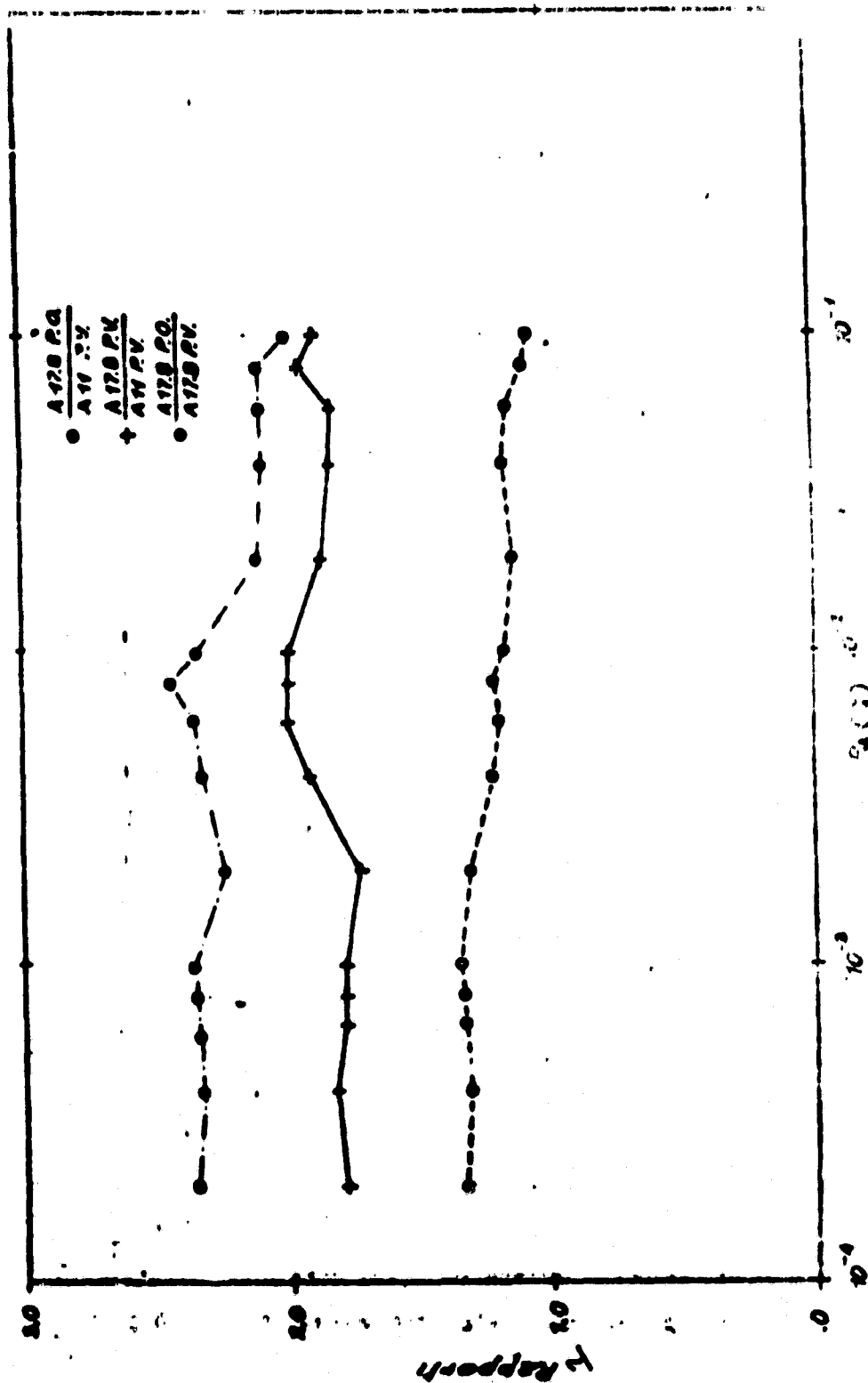


Figure 27. Slopes of Relationships with Various Degrees of Attenuation, with Equal Percentage, Derived from the Mean Distributions in Figure 2.

Key: 1-Relationships